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ABSTRACT

This training manual consists of two parts. The first covers general information and outlines various applications of food irradiation technology. The second section details laboratory exercises used to demonstrate the principles of radiation processing and the effects of radiation treatment on certain types of food. The chapters outline radioisotopes and radiation, radiation detection and measurement, health physics, radiation chemistry, effects of radiation on living organisms, preservation of foods, radiation preservation of foods, packaging, wholesomeness of irradiated foods, government regulation of irradiated foods, food irradiation facilities, commercial considerations of food irradiation, and related literature. (Diagrams, graphs, data tables, and illustrations are included.) (KP)

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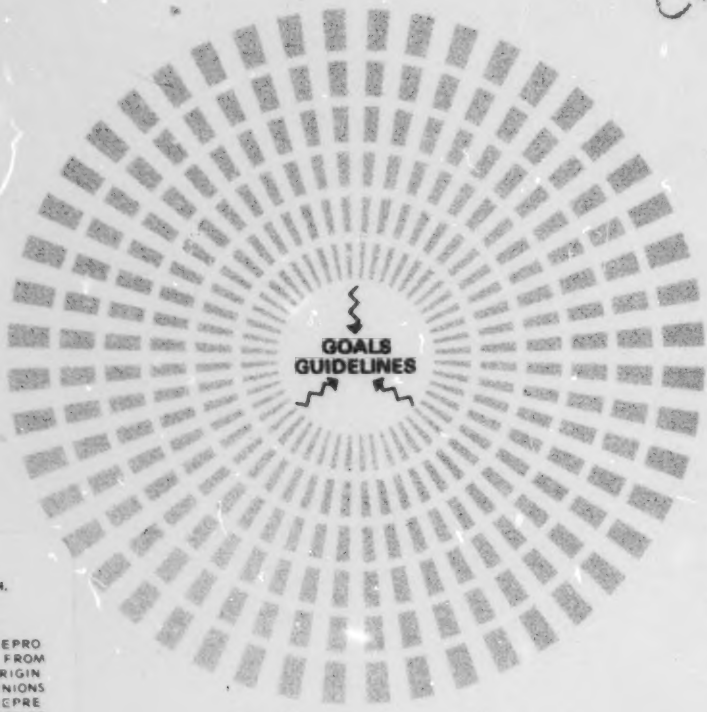

TECHNICAL REPORTS SERIES No. 114

Training Manual on Food Irradiation Technology and Techniques

JOINT FAO/IAEA DIVISION OF
ATOMIC ENERGY IN FOOD AND AGRICULTURE

INTERNATIONAL ATOMIC ENERGY AGENCY, VIENNA, 1970

TRAINING MANUAL ON FOOD IRRADIATION TECHNOLOGY AND TECHNIQUES

TECHNICAL REPORTS SERIES No. 114

TRAINING MANUAL ON FOOD IRRADIATION TECHNOLOGY AND TECHNIQUES

A JOINT UNDERTAKING BY THE
FOOD AND AGRICULTURE ORGANIZATION
OF THE UNITED NATIONS AND THE
INTERNATIONAL ATOMIC ENERGY AGENCY

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 1970

FOREWORD

In the last 16 years ionizing radiation has come into use as a means of preserving food. This method has been described as the only new and novel food process developed since the invention of food canning by Nicholas Appert in France approximately 150 years ago. It is attractive because it works without heating the product, is effective within sealed containers as well as in bulk, and does not leave chemical residues on the food products. Research on the feasibility of preserving many types of food by this means is being carried out in over 50 countries.

The need for food irradiation technologists became so apparent that the International Atomic Energy Agency, the Food and Agriculture Organization of the United Nations and the United States Atomic Energy Commission sponsored a Training Course on Food Irradiation Technology and Techniques in 1967, in co-operation with the Michigan State University at East Lansing, Michigan, USA. The success of this course prompted the three organizations to sponsor a second Training Course in 1969 in co-operation with the Massachusetts Institute of Technology, Cambridge, Massachusetts, USA.

The success of these two training courses has prompted the IAEA and FAO to prepare this training manual for use in future training courses.

The present manual consists of two parts:

I. The basic part, covering general information and discussions on the applications.
II. A section on laboratory exercises to demonstrate the principles of radiation processing and the effects of radiation treatment on certain types of food.

The manual should prove of value not only to those associated with the IAEA and FAO training programs, but also to other research scientists in countries working on the development of food preservation, or on the introduction of the irradiation process into the food industry. It is hoped that the manual will help to bring about a better understanding of the process internationally.

Previous manuals in this series sponsored by the IAEA and FAO and published by the IAEA, are:

TRS No. 29: Laboratory training manual on the use of isotopes and radiation in soil-plant relations research (1964).
TRS No. 60: Laboratory training manual on the use of isotopes and radiation in animal research – second edition (1969).
TRS No. 61: Laboratory training manual on the use of isotopes and radiation in entomology (1966).

The IAEA and FAO would like to convey their appreciation to Dr. Walter Urbain of the Michigan State University for preparing the major portion of the manual, and to Drs. Samuel A. Goldblith, Joseph Licciardello and Antony J. Sinskey, of the Massachusetts Institute of Technology, for their valuable contributions to part of it.

The manuscript in its final form has been prepared by Dr. Harry E. Goresline, in consultation with Dr. M. de Proost of the Joint FAO/IAEA Division of Atomic Energy in Food and Agriculture, Vienna.

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GLOSSARY OF TERMS
FREQUENTLY USED IN THIS MANUAL

TERM	SYMBOL	DEFINITION
Alpha particle	α	A positively charged particle emitted from a nucleus and composed of 2 protons and 2 neutrons. It is identical in all measured properties with the nucleus of a helium atom.
Beta particle	β^+ or $^-$	A charged particle emitted from the nucleus during radioactive decay and having a mass and charge equal in magnitude to those of the electron. A negatively charged beta particle is physically identical to the electron.
Curie	Ci	A basic unit used to describe the intensity of radioactivity. One Curie equals 3.7×10^{10} disintegrations per second, or approximately the radioactivity of 1 gram of radium.
Decimal reduction	D_{10}	The radiation dose in rads to reduce a population (e.g. of bacteria) by a factor of 10, or one log cycle (10% survivor).
Dose	D	The amount of ionizing radiation absorbed by a material.
(OH) $\bullet$	$\bullet$	The $\bullet$ indicates a free radical.
Electron	e^-	A negatively charged particle that is a constituent of all atoms.
Electron volt	eV	The amount of kinetic energy gained by an electron accelerated through an electrical potential difference of one volt.
G value		Number of molecules charged per 100 eV energy transferred to the system.
Gamma ray	γ	A high-frequency electromagnetic radiation produced when an unstable atomic nucleus releases energy to gain stability.
Induced radioactivity		Radioactivity resulting from certain nuclear reactions in which exposure to radiation results in the production of unstable nuclei, which through spontaneous disintegrations give off radiation.
Ion		The atomic particle, atom, or chemical radical bearing an electrical charge, either positive or negative, caused by an excess or deficiency of electrons.
Ionization		The process of adding to or knocking electrons from, atoms or molecules, thereby creating ions.
Isotope		Atoms of the same chemical element having the same atomic number but with different atomic weights, or those with nuclei having the same number of protons but different numbers of neutrons. A radioisotope is an unstable isotope that decays or disintegrates spontaneously, emitting radiation.

TERM	SYMBOL		DEFINITION
Radiation absorbed dose	rad		The basic unit of absorbed dose of ionizing radiation. It equals 100 erg of absorbed energy per gram of absorbing material. The rad has replaced the former unit rep.
Roentgen	R		The dose of Gamma or X-radiation producing ion pairs carrying one electrostatic unit of charge per cm^3 of standard air surrounded by air. It equals 83.8 erg per gram of air.
Roentgen equivalent man	rem		A unit of absorbed radiation. It is equal to the absorbed dose in rads multiplied by the relative biological effectiveness of the radiation.
Roentgen equivalent physical	rep		An obsolete term for the radiation dose in material other than air.
Unit prefixes			
pico	p	10^{-12}	
micro	µm	10^{-6}	
milli	m	10^{-3}	
kilo	k	10^{3}	
mega	M	10^{6}	
X-rays			X-rays are produced when high-energy charged particles impinge on a suitable target.

PART I

LECTURE MATTER

LECTURE MATTER

1. RADIOISOTOPES AND RADIATION

Let us start the study of the ionizing radiation phenomenon that is the basis for the food irradiation process by discussing the atomic model.

1.1. Atomic model: Definitions

An atom is composed of a positively charged nucleus which is surrounded by shells of negatively charged (orbital) electrons. The nucleus contains protons and neutrons as its major components of mass; the former have a positive charge, and the latter have no charge. The nucleus has a diameter of approximately 10^{-12} cm and contains almost the entire mass of the atom. The atom including the orbital electrons has a diameter of approximately 10^{-8} cm or 1 Ångström unit (Å).

The number of protons in the nucleus (Z) is characteristic for a chemical element. The atoms of a particular element may, however, not all have the same number of neutrons (N) in the nucleus. Atom types that have the same Z- but different N-values are called isotopes of the same element. As the neutrons and protons represent the major part of the mass of the atom and each has an atomic weight close to unity, the mass number, which is the sum of protons and neutrons, is close to the atomic weight M.

$$\text{Mass number} = Z + N \doteq M$$

The nuclei of some isotopes are not always stable; they disintegrate spontaneously at a characteristic decay rate. In nature a number of unstable isotopes are known, and nowadays many unstable isotopes are produced artificially in atomic reactors and by particle accelerators. As the disintegration of unstable isotopes is accompanied by the emission of various kinds of radiation, these unstable isotopes are called radioisotopes.

The nuclei of radioisotopes may emit α-, β^+-, β^-- and γ-rays. α-particles are fast-moving He nuclei, each containing two protons and two neutrons. β^+- and β^--particles are, respectively, positively and negatively charged, high-speed electrons, while γ-rays are electromagnetic wave packets (photons) of very short wave-length compared with visible light, but travelling at the speed of light.

Natural isotopes of low Z (except ordinary hydrogen) have approximately the same number of neutrons as protons ($N \doteq Z$) in their nuclei, and they are usually stable. As the atomic number of the elements increases, the number of neutrons increasingly exceeds the number of protons, which finally results in unstable nuclei. Thus, the majority of unstable isotopes in nature is found for elements of high Z-number with a neutron:proton ratio of the order of $1\frac{1}{2}$:1. The emission of α-particles is characteristic of these elements. The combination of two protons and two neutrons is one of the very stable nuclear forms; and

this combined form, the α-particle, is ejected as a single particle from the nucleus of the radioactive atom.

There appears to be a more or less well-defined optimum N/Z ratio for the stability of each element. When the number of neutrons in the nucleus of a radioisotope is excessive, the number of protons in the nucleus tends to increase by the ejection of a negative β-particle from the nucleus. This beta particle accompanies the transformation of neutron into proton:

$$n \rightarrow p^+ + \beta^- \text{ (+ neutrino)}.$$

An excess of protons in a nucleus may be counteracted by the ejection of a positron, a positively charged electron (regarding MeV, see section 1.3. below):

$$p^+ + 1.02 \text{ MeV} \rightarrow n + \beta^+ \text{ (+ anti-neutrino)}.$$

Excess of protons in the nucleus may alternatively be reduced by the capture of an orbital (valence) electron (K-capture):

$$p^+ + e^- \rightarrow n.$$

This process is accompanied by the emission of a characteristic X-ray, representing the energy difference between L- and K-shell electron in the element formed, since the "hole" in the K-shell is filled by an L-electron.

After the ejection of an alpha or beta particle, or K-capture, the energy level of the daughter nucleus may not be at its ground state. The excess energy of this excited nucleus is emitted in the form of one or more gamma photons.

A gamma photon may interact with an orbital electron in the decaying atom, whereby the electron is ejected from the atom at a given velocity and the photon ceases to exist. This process results in the combined emission of a fast electron and a characteristic X-ray and is known as "Internal Conversion".

When a large nucleus such as ^{235}U captures a neutron, the nucleus will divide into two parts of approximately similar masses. This process is called "fission". All the primary fission products are unstable (excessive N), and each forms a series of radioactive daughter isotopes terminating with a naturally occurring stable isotope.

Summarizing, we may say that radioisotopes will emit particles and/or photons of the following nature:

α-particle	- doubly positively charged particle, containing two neutrons and two protons and originating at high speed from the nucleus;
β^--particle	- high-speed electron from the nucleus, negatively charged;
β^+-particle	- high-speed positron from the nucleus, positively charged;

γ-ray photon	- electromagnetic energy packet coming from the nucleus at the speed of light;
X-ray photon	- electromagnetic energy packet coming from an electron shell at the speed of light, following K-capture or Internal Conversion;
IC electron	- (Internal Conversion electron) electron emitted as a result of the interaction between a γ-ray and a valence electron;
neutron	- particle with no charge and a mass close to that of a proton.

1.2. Radioactive decay and "specific activity"

The number of disintegrations per unit increment of time is a constant fraction of the number of radioactive atoms present at that time. Mathematically this can be expressed as

$$D^* = -\frac{dN^*}{dt} = \lambda^* N^*, \qquad (1)$$

where D^* is the disintegration rate (expressed per minute) at time t,
N^* is the number of radioactive atoms present at time t, and
λ^* is the decay constant expressed in reciprocal minutes.

The minus sign indicates that the number of radioactive atoms decreases with time t. Integrating the differential equation (1) and calling the number of radioactive atoms present at beginning time N_0, one obtains

$$N^* = N_0^* e^{-\lambda^* t} \quad \text{or} \quad D^* = D_0^* e^{-\lambda^* t} \qquad (2)$$

It follows from equation (2) that the time required for one-half of the original activity to decay is independent of the beginning number of atoms. Designating the time required for half decrease of original activity as $t_{\frac{1}{2}}$, one obtains

$$\tfrac{1}{2} D_0^* = D_0^* e^{-\lambda^* t_{\frac{1}{2}}}; \quad \text{i.e. } \lambda^* t_{\frac{1}{2}} = \ln 2 = 0.693,$$

where $t_{\frac{1}{2}}$ is the "half-life" of the isotope expressed in minutes. It is seen that the product of decay constant and half-life of any isotope is 0.693, which is useful for conversion of $t_{\frac{1}{2}}$ to λ^*. The decay constant, having the dimension of reciprocal time and being generally a small number, is inconvenient for many purposes. Instead, half-life ($t_{\frac{1}{2}}$ in, e.g., days or years) is often used as the decay characteristic of a radioisotope.

The practical unit of absolute (radio)activity is the curie, equal to 3.70×10^{10} disintegrations per second (approximately equal to the disintegration rate of 1 g of radium). One curie (Ci) is thus equal to 2.22×10^{12} dis/min, one millicurie (mCi), one microcurie (μCi) and one picocurie (pCi), 2.22×10^{9}, 2.22×10^{6} and 2.22 dis/min. One

kilocurie (kCi) and one megacurie (MCi) equal 2.22×10^{15} and 2.22×10^{18} dis/min, respectively.

If one has g* grams of a radioisotope with a decay constant λ^* and an atomic weight of M, the radioactivity expressed in curies will be as follows (N^0 is Avogadro's number):

$$\frac{g^*}{M} \times N^0 = \text{Total number of radioactive atoms } (N^*)$$

$$\lambda^* \times \frac{g^*}{M} \times N^0 = \text{Total disintegrations per minute } (D^*)$$

$$\lambda^* \times \frac{g^*}{M} \times \frac{N^0}{2.22 \times 10^{12}} = \text{Total activity in curies.}$$

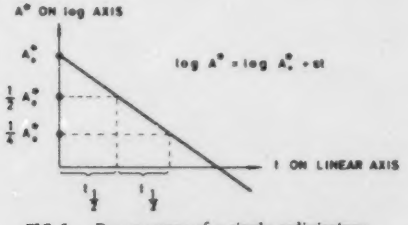


FIG. 1. Decay curve of a single radioisotope

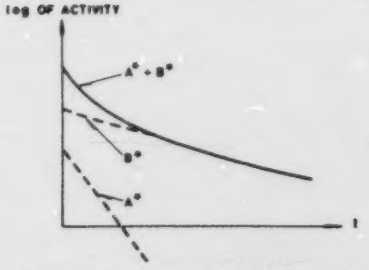


FIG. 2. Decay curve of two radioisotopes. A and B, simultaneously present in a sample

The decay constant or the half-life of an isotope can be graphically determined if the half-life is within a measurable range. It appears from equation (2) that, if the measured activity, $A^* = YD^*$ (where Y is the constant counting yield), is plotted against time on semi-log paper, a straight line will be observed. The half-life or decay constant can easily be found directly (see Fig.1) or from the slope s, which is equal to $-\lambda^*/2.3$. For isotopes of very long half-life, one has to apply the method of absolute measurement for half-life determination.

When two radioisotopes, "A" and "B", are present simultaneously, the observed activity is

$$A_0^* e^{-\lambda_A^* t} + B_0^* e^{-\lambda_B^* t}$$

If this activity is plotted on semi-log paper, one obtains a composite curve, such as appears in Fig.2. With the assumption that the half-lives are sufficiently different (e.g. a factor of 10), the curve can be resolved graphically by subtraction of the extrapolated straight line resulting from the long-lived component (B) from the sum curve observed. The two straight lines then yield the two half-lives.

In practice, a radioisotope will be accompanied by a variable quantity of stable isotopes of the same element. The stable form is called "carrier". To specify the concentration of radioisotope in one element or compound, the term specific activity is introduced. This is generally expressed as radioactivity per unit amount of specified test substance.

By some procedures radioisotopes can be prepared virtually free from carrier, in which case they are called "carrier-free".

1.3. Energy of radiation

The energy unit commonly used with regard to radiation is the electron volt (eV). This is equivalent to the kinetic energy acquired by an electron on being accelerated through a potential difference of one volt. 1 keV and 1 MeV are 10^3 eV and 10^6 eV, respectively; 1 MeV is equal to 1.6×10^{-6} erg.

The kinetic and total energies, respectively, of the particles and photons emitted by radioisotopes have characteristical values, which are usually indicated for each isotope on nuclear charts. Any energy spectrum of the alpha particles, gamma photons or characteristic X-ray photons emitted by a radioisotope is discrete, showing one or a few monoenergetic ("monochromatic") lines. On the other hand, the energy of beta particles ejected by a given isotope varies from zero up to a certain maximum energy ($E_{max.}$) that is at the disposal of the beta particle. This is because a variable part of $E_{max.}$ is taken away by a neutrino or an anti-neutrino, neither of which is observable in ordinary counting (they have no charge and practically no mass). As a consequence, the beta particles show a continuous spectrum of energies from zero up to the characteristic $E_{max.}$. The beta energies given in a table or chart of isotopes are $E_{max.}$-values; the average beta-particle energy is usually about one third $E_{max.}$. The continuous beta spectrum may sometimes be overlapped by one or two monoenergetic lines from IC electrons.

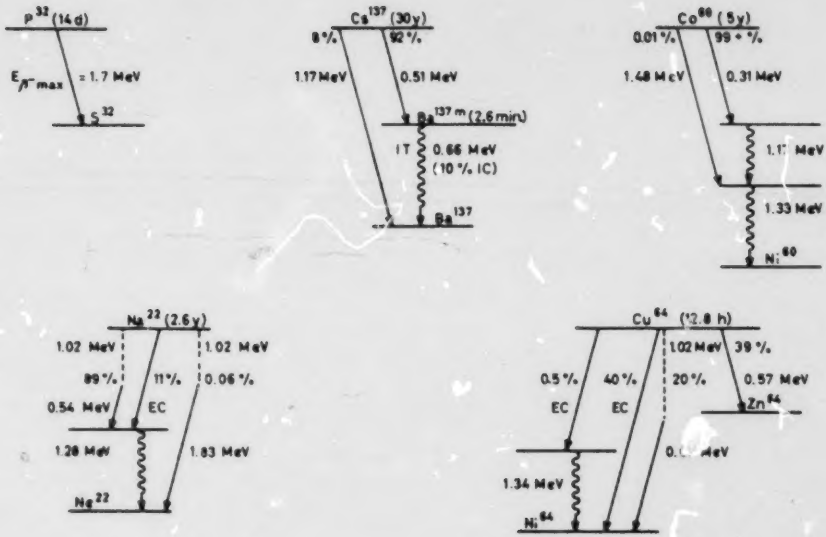
The characteristic radiations and energies for a given radioisotope are often shown in the form of decay schemes (for example, see Fig.3).

A knowledge of decay characteristics is important in considerations on protection against, and measurement of, radioisotopes.

Radioisotope sources of ionizing radiation are of interest in connection with food irradiation primarily as sources of beta and gamma radiation. Alpha rays from radioisotopes do not have properties which make them useful for food irradiation.

1.4. Machine sources of radiation

Machine sources of electron beams and possibly of X-rays provide radiation which can be effectively utilized to produce ionizing radiation.



Key

↘	β^--particle
↙	β^+-particle
EC	electron capture (K-capture)
↓	γ-photon
h	hour(s)
d	day(s)
y	year(s)
Ba^{137m}	excited Ba^{137}, called "metastable" because the emission of the γ-ray is not instantaneous
IT	Isomeric Transition. Different types of the same isotope are called isomers
I.C.	Internal Conversion

FIG. 3. Disintegration schemes showing characteristic radiations and energies of five different radioisotopes

All such machine sources are primarily electron beam generators. By directing the electron beam into a suitable target material, X-rays can also be generated. All of these generators utilize the negative electric charge of the electron to impart energy to the electron through the application of an accelerating voltage. Except in the case of the linear accelerator, the full direct current accelerating potential is developed. This limits the practical potentials to below about 4 million volts. The linear accelerator, not having this limitation, is useful above 4 million

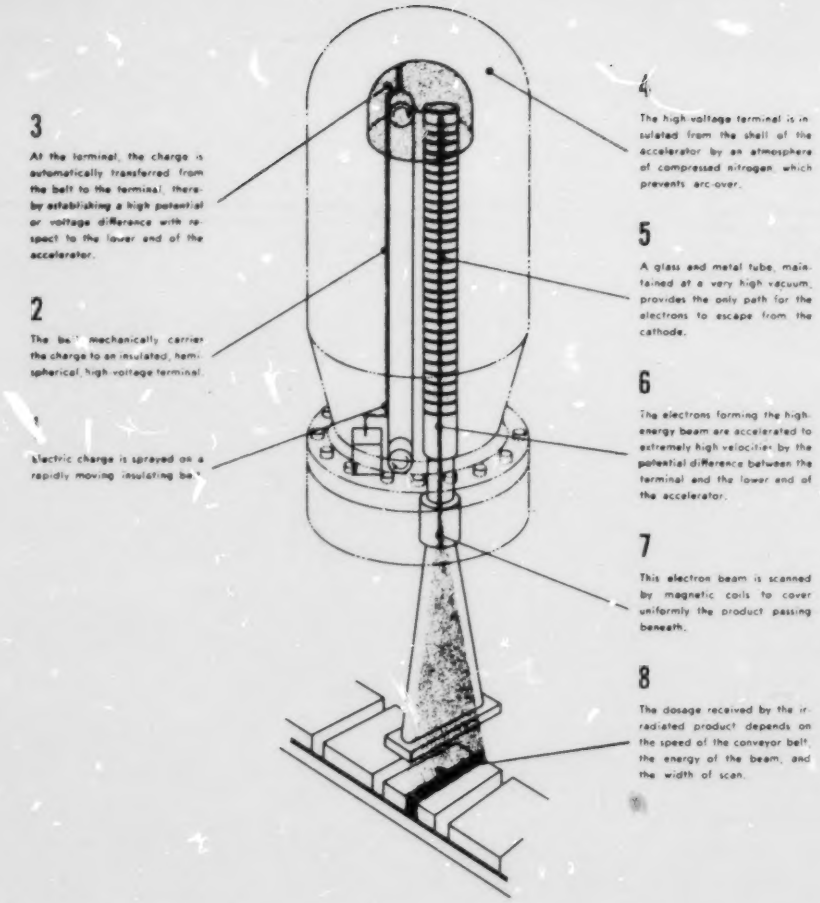

3
At the terminal, the charge is automatically transferred from the belt to the terminal, thereby establishing a high potential or voltage difference with respect to the lower end of the accelerator.
2
The belt mechanically carries the charge to an insulated, hemispherical, high-voltage terminal.
1
Electric charge is sprayed on a rapidly moving insulating belt.
4
The high-voltage terminal is insulated from the shell of the accelerator by an atmosphere of compressed nitrogen which prevents arc-over.
5
A glass and metal tube, maintained at a very high vacuum, provides the only path for the electrons to escape from the cathode.
6
The electrons forming the high-energy beam are accelerated to extremely high velocities by the potential difference between the terminal and the lower end of the accelerator.
7
This electron beam is scanned by magnetic coils to cover uniformly the product passing beneath.
8
The dosage received by the irradiated product depends on the speed of the conveyor belt, the energy of the beam, and the width of scan.

FIG. 4. Van de Graaff accelerator

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volts. Principal parts of each generator are the electron source and acceleration tube. Electrons are obtained from a hot wire (or cathode) and are subjected to the accelerating potential within the confines of an envelope or tube providing a vacuum. They emerge into air after penetrating a suitable tube window.

The depth of penetration of such beams into matter is limited to the equivalent of 0.5 cm of water per million electron volts (MeV). Thus, 2 MeV are required to penetrate 1 cm of water, or its equivalent in food, depending on the relative density.

We will now consider several machine sources.

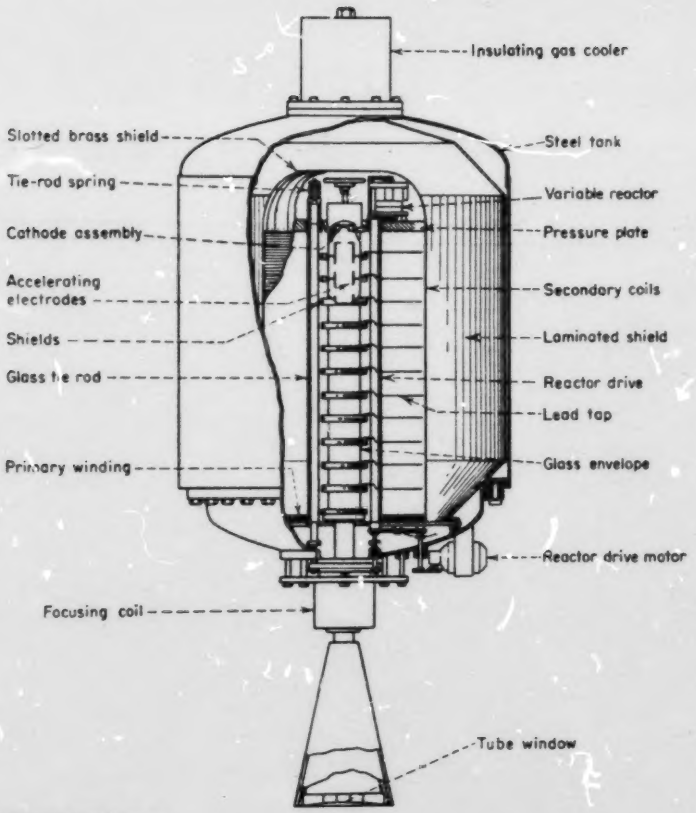

FIG.5. Resonant transformer

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1.4.1. Van de Graaff accelerator

This accelerator is portrayed schematically in Fig.4. Within a pressurized housing, a corona discharge is directed onto an endless belt of non-conducting material. The resultant "charge" is physically conveyed to the upper part of the housing and transferred to an isolated conductive shell. By accumulation of sufficient "charge" this shell develops a high potential, which is applied to the acceleration tube and to the electrons. The Van de Graaff accelerator delivers a constant current of monoenergetic electrons.

1.4.2. Resonant transformer

This accelerator is portrayed schematically in Fig.5. The high voltage is obtained from a step-up transformer in which the secondary

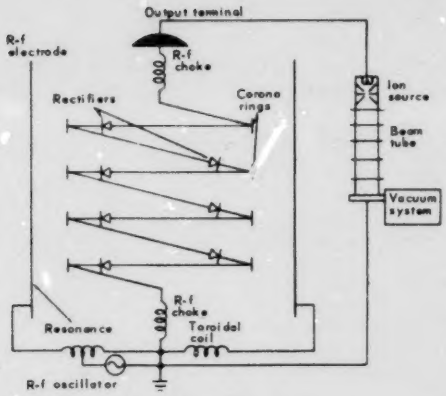

FIG.6. Schematic diagram of dynamitron

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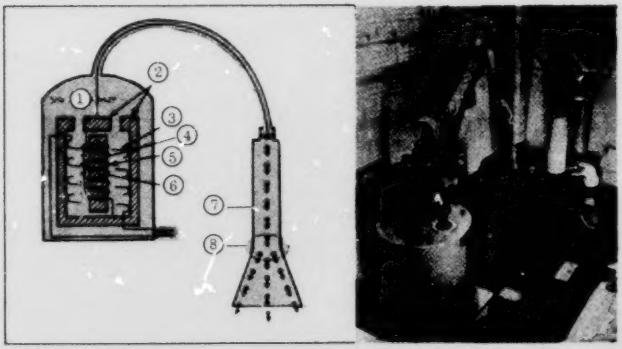

1	GAS INSULATION	5	SECONDARY COIL
2	TRANSFORMER CORE	6	RECTIFIER TUBE
3	PRIMARY COIL	7	ACCELERATOR VACUUM TUBE
4	DISTRIBUTED CAPACITY	8	ELECTRON BEAM SCANNING SYSTEM

FIG.7. Insulating core transformer

winding is tuned to resonance. This eliminates the need for the iron core, which would be too large for transformers in the voltage and current range required. The voltage is applied in a fashion similar to that of the Van de Graaff accelerator. The electron beam is pulsed and the electrons have a range of energies.

1.4.3. Dynamitron

This accelerator is portrayed schematically in Fig.6. This accelerator utilizes a cascaded rectifier system in which all rectifiers are driven in parallel from a high frequency oscillator. Four large

r-f electrodes situated inside a cylindrical pressure vessel draw power from the oscillator. The r-f potential is capacitively coupled to corona rings attached to each rectifier tube through a high pressure dielectric gas. The direct current from the rectifiers establishes a large d.c. potential which is applied to the system as with other electron beam generators. The monoenergetic electron beam thus developed is essentially of constant current.

1.4.4. Insulating core transformer

This accelerator is portrayed schematically in Fig.7. This is a three-phase power transformer with multiple secondaries, each of which is insulated from each other. The alternating current in each secondary is rectified and the individual direct current outputs are connected in series to provide the high voltage for acceleration of the electrons. This high voltage is utilized through a conventional tube, and the output is essentially a constant current of monoenergetic electrons.

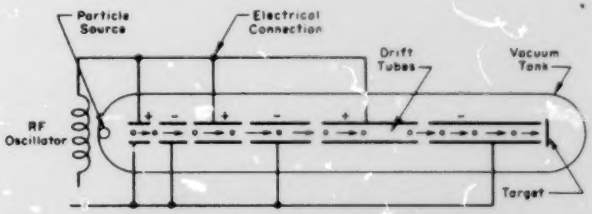

FIG.8. A linear accelerator. The separation between accelerating gaps, which is the distance traversed by the particles during one half cycle of the applied electric field, becomes greater as the velocity of the particle increases. At any instant adjacent electrodes carry opposite electric potentials. These are reversed each half cycle.

1.4.5. Linear accelerator

This kind of accelerator exists in several forms. Electrons are given energy by properly phased sequential exposure to a given potential difference or, alternatively, by keeping continuously in step with a moving electromagnetic field. This approach avoids the limitations imposed by the ability to handle the full accelerating potential. Consequently energies greater than 4 MeV can be given to electrons. One form of this accelerator is portrayed schematically in Fig.8. The essentially monoenergetic electron beam is pulsed.

1.4.6. X-ray source

When high energy electrons strike a metal target, X-rays are formed. Part of the X-radiation is emitted at a frequency characteristic of the target material and also related to the energy of the impinging electron. In addition, a substantial proportion of the energy is emitted as a continuous X-ray spectrum; the upper energy limit of this is again dependent

upon the target material and the impinging electron energy, according to the equation

$$h\nu = eV$$

The conversion efficiency of electrons to X-rays depends upon the target material and the electron energy. This relationship for aluminium and tungsten is shown in Table I.

The relatively low efficiency for converting electrons to X-rays is not necessarily a deterrent to the use of this kind of source. The high penetrating power of X-rays is of great advantage in certain applications. Convenience, the rather widespread availability of X-ray equipment and indications of competitive costs on a unit energy basis suggest serious consideration of X-rays.

1.5. Interaction of radiation with matter

1.5.1. Absorption of alpha particles

The alpha particles ejected from any particular radioisotope are monoenergetic. In passing through matter and interacting with the atoms thereof, the kinetic energy of the alpha particle will be spent in (1) exciting outer shell electrons to higher-energy orbits, and (2) ejecting electrons out of their orbits. Since alpha particles are doubly charged and the mass is relatively large (atomic weight 4), a dense track of ion pairs (i.e. ejected electrons and positively charged atom residues) is formed along the path of an alpha particle. As the alpha particle dissipates its energy along its path, the velocity of the particle decreases and finally the particle acquires two electrons from its surroundings and becomes a helium atom. The range, i.e. the distance that an alpha particle can penetrate into any matter (absorber), depends on the initial energy of the particle and the density of the absorber. The range of the alpha particle is generally small and amounts to several centimetres in air and several microns (10^{-3} mm) in aluminium for energies of the order of 1 - 10 MeV. As the energy of an alpha particle is lost in a relatively

TABLE I. CALCULATED CONVERSION EFFICIENCIES FOR X-RAY PRODUCTION

Electron energy (MeV)	Conversion efficiency (%)	
	Aluminium	Tungsten
10.0	7.7	30
5.0	4.0	19
3.0	2.5	14
2.0	1.8	10
1.0	0.9	6
0.5	0.4	3

thin layer of absorber, it is evident that the number of ion pairs per centimetre of track, the specific ionization, is very high.

1.5.2. Absorption and scattering of beta particles

Beta particles cause excitations and ionizations in matter just as do alpha particles, but the mass of the beta particle is only 1/7000 of the mass of the alpha particle and beta particles have half the charge per particle. They will therefore scatter more, penetrate relatively deeper into matter and have a lower specific ionization. As does the alpha particle, the beta particle has a "range" (i.e. a maximum penetration depth into an absorber) which is characteristic of the initial energy of the particle and the density of the absorber, but this range is not so well defined because of the zig-zag path (scattering) of the electron as compared with the straight path of the helium nucleus.

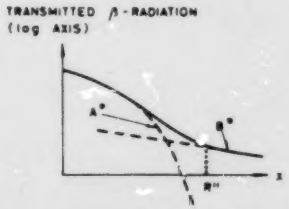

FIG.9. Curve demonstrating the transmitted β-radiation as a function of absorber thickness

Because of the fact that beta particles have a continuous spectrum of energies up to an $E_{max.}$, their absorption in matter is at best only approximately exponential and obeys the following equation only crudely:

$$A^* = A_0^* e^{-\mu x}$$

where A_0^* is the activity (intensity) of the incident radiation,
A^* is the activity (intensity) of the transmitted radiation,
μ is the β-absorption coefficient of the absorber, and
x is the thickness of the absorber.

Therefore, when the radiation transmitted by the absorber is plotted as a function of the absorber thickness on semi-log paper, a fairly straight line is obtained over a portion of the curve (Fig.9).

The curve becomes practically horizontal at "R", the "range" for beta particles with $E_{max.}$. Although all the beta rays are stopped at this absorber thickness, one still finds some transmission of radiation, because, particularly at low velocities, the beta particles interact with the atoms of the absorber, giving rise to (non-characteristic) X-rays, the so-called "bremsstrahlung" (B*). By subtraction of B* from the composite curve, the pure beta transmission curve (A*) is obtained.

Positron energy absorption takes place in the same manner as for negative beta radiation. However, when the kinetic energy of the positron becomes very low, the positron is annihilated together with

an electron, giving rise to two characteristic photons of 0.51 MeV each; $e^+ + e^- \rightarrow 2$ photons.

Absorption and scattering of beta particles is important in the measurement of beta-active samples. Absorption and scattering will occur in a sample cover or a detector window as well as in intervening air. Side-scattering (into the detector) from a counter shield and/or back-scattering from a sample support will also occur. These effects will all influence the counting rate one way or the other. Finally, unless the sample is "infinitely" thin, self-scattering (into and away from the detector) and self-absorption will all take place in the material of the sample itself, and this will cause an overall self-weakening effect, which is largest for thick samples and small (even slightly negative) for very thin samples. The counting rate from samples of increasing thickness at first increases because of greater total activity and then becomes constant (at "infinite" thickness) because the contribution of beta activity from the lower layers of the sample is entirely absorbed in the upper ones.

1.5.3. Attenuation of gamma and X-rays

In passing through matter, the energy of gamma and X-ray photons is attenuated by three important interactions: (1) photoelectric effect, (2) Compton scattering and (3) pair-production.

(1) When the photon energy is below about 0.5 MeV, the photoelectric effect is predominant. The total energy (i.e. the entire photon) is used up in the ejection of an electron at high speed from an atom shell. Subsequently, this fast electron causes many excitations and ionizations just as does a beta particle. The photoelectric effect is particularly important when the atoms of the absorber have a high Z-number.

(2) Compton scattering arises predominantly when gamma photons in the energy range 0.5 - 5 MeV collide with free or loosely bound electrons in the absorber. Part of the photon energy is transferred to the electron as kinetic energy in such a collision, and the reduced photon is deflected (slightly or up to 180°) from its original direction. This effect is important for absorber atoms of high Z-number.

(3) When a photon has an energy of at least 1.02 MeV or higher, it may become extinct in the proximity of an atomic nucleus of the absorber, giving rise to an electron-positron pair. Any photon energy above the required 1.02 MeV is imparted to the e^- and the e^+ as kinetic energy.

Theoretically, gamma or X-radiation is never completely stopped by matter although the transmitted radiation may be reduced to an insignificant value. For a collimated beam of monoenergetic photons, attenuation by absorption and scattering can be described mathematically as follows:

$$I = I_0 e^{-\mu x}$$

where I_0 is the initial intensity of collimated monoenergetic photons,
I is the intensity after passing x cm of the absorber, and
μ is the attenuation coefficient for the photon energy and the material concerned.

This is the well-known Lambert-Beer law for visible light photons. The derivation of the equation from the basic assumption that

$$-\frac{dI}{dx} = \mu I$$

is analogous to the derivation of the radioactive decay law $N^* = N_0^* e^{-\lambda^* t}$ (see section 1.2.). The thickness at which I_0 is reduced to half its intensity is called the "half-thickness" (analogous to half-life). If the half-thickness is expressed as mass-thickness (g/cm^2), its value is a function of the energy of the gamma photons but, for 0.5 - 5 MeV photons, largely independent of the type of material.

An understanding of photon interaction with matter is useful in considerations on shielding, body dose and measurement.

1.5.4. Scattering and absorption of neutrons

Neutrons, being without charge, lose energy only by direct contact with nuclei of matter. The processes may be of the following four types:

(1) Of an elastic nature, like billiard-ball collisions. Ion pairs are produced by these collisions, the hit nucleus loosing one or more of its orbital electrons. Neutrons of high initial energy (fast neutrons) gradually lose their energy by this interaction until they have been moderated to "slow" or "thermal" neutrons. Light elements, especially H, have the best neutron moderating qualities.

(2) Of a type in which the neutron is absorbed by nuclei with resultant nuclear reaction. This occurs predominantly with slow neutrons, e.g.

$$^{10}B + n \rightarrow (^{11}B) \rightarrow {}^{7}Li + \alpha + \gamma.$$

(3) When the nuclei of certain elements of high atomic number are hit by neutrons of appropriate energy, fission results (the nuclear pile).

(4) Finally, free neutrons decay spontaneously, with a half-life of 12 min, to protons and beta particles, which thereupon excite and ionize atoms of matter.

1.5.5. Induced radioactivity

When ionizing radiation impinges on matter, energy may be imparted to the nuclei of some of the atoms. Under certain conditions, this may cause excitation sufficient to induce an atomic nucleus to become so unstable that it emits a neutron, together with gamma radiation. This reaction changes the atomic nucleus into that of a different element or that of an isotope of the original one. In this way, ionizing radiation may induce the appearance of radioactivity in matter, which previously showed virtually none. The possibilities of producing such induced radioactivity depend on the properties of the matter irradiated and on the energy of the radiation employed. If the energy of the radiation source is sufficiently high, several of the elements contained in food can be made radioactive. For example, at an energy level of 10.5 MeV, the

nucleus of ordinary ^{14}N can be induced to eject a neutron with the production of a radioisotope of nitrogen; ordinary ^{16}O can be induced to undergo such a change when irradiated at an energy level of 15.5 MeV, and ordinary ^{12}C can be induced to make such a change at an energy of 18.8 MeV.

Since these elements are among the principal elements contained in food, it is important that they do not become radioactive. It is for this reason that particular radiation sources have been selected for the irradiation of foods. At the present time, the radiation sources permitted are: (1) ^{60}Co; (2) ^{137}Cs; (3) Accelerated electrons of not more than an energy of 10 MeV and (4) X-rays from a source with a beam energy of not more than 5 MeV. It has been amply demonstrated that there is no danger of inducing radioactivity in food with such selected sources.

2. RADIATION DETECTION AND MEASUREMENT

Ionizing radiation interacts with all matter (gaseous, liquid or solid), causing chemical changes, ionizations and excitations. These effects are utilized in the various methods of detection and measurement.

In radiography, for example, ionizing radiations are detected by their effect on photographic emulsions. In the ionization chamber, the gas-flow detector, the Geiger-Müller tube and the neutron detector, and ions produced directly or indirectly by the radiation are collected on charged electrodes. In solid and liquid scintillation counting, emission photons (in the blue ultra-violet region) form the basis of detection. Certain chemical reactions produced by ionizing radiation can be used to measure the amount of radiation. Since absorbed ionizing radiation degrades to heat, calorimetry can be employed for quantitative measurement of radiation.

A number of detector and measuring systems will now be described.

2.1. Detection by ionization

A number of detectors are based on the principle that, in an electric field, negative particles will move to a positive electrode and positive particles to a negative electrode. Charged particles which arrive at an electrode will give rise to an electronic pulse, which can be amplified and registered. Alternatively, the pulses may be merged to form an electric current, which again can be amplified and measured.

Alpha and beta particles and IC electrons (e) have a high specific ionization, i.e. produce a great number of ion pairs per unit length of track. Gamma- and X-rays have a much lower primary specific ionization; but at least one fast electron will be released by each photoelectric effect or Compton scattering (or pair production if the energy is very high), and these fast electrons will ionize just as do β-particles. Neutrons may also produce ions, directly (collision) or indirectly (following nuclear absorption), as described in section 1.5.4. above. Detection by ionization of these kinds of radiation is based on the fact that atoms of a gas (in the detector) will become ionized when they are hit by the radiation particles or photons. The number of ionizations in the gas is a direct

measure of the quantity of ionizing particles or photons (α, β, e, γ, X or n) that reach the detector. When an electric field is created in the detector, the negative ions (electrons) will start moving and by hitting the positive electrode (anode) discharge. Likewise the positive ions will move towards the cathode.

Four different types of ionization instrument will now be described.

2.1.1. Electroscope

In the electroscope or simple electrometer (see Fig.10) the positive electrode is a rod with a wing or a metal string, and the negative electrode is the wall of the detector.

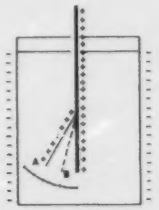

FIG.10. Electroscope

When the electroscope is fully charged, the deflection of the wing or string will be maximal (A), the amount of deflection being a function of the charge accumulated. When a radioactive source is brought near the detector, the air in the detector will become ionized and electrons will move in the direction from wall to rod. As a consequence, the deflection will decrease (B).

This type of detector is commonly used as a "pocket dosimeter" and gives a measure of the accumulated dose of external radiation (γ-, X- and hard β-radiation) to which a worker has been exposed during a certain period.

2.1.2. Ionization chamber

Not all the ions will discharge on the electrodes of an electroscope. A certain number will recombine before they have reached the electrodes. If the voltage applied to the electrodes is steadily increased, the losses resulting from recombination will decrease, and eventually all the ions will discharge on the electrodes of the detector. If the voltage difference between the electrodes is further increased up to a certain limit, the number of ion pairs that discharge will remain constant. Each ionizing particle or photon will thus give rise to an electric pulse on the electrodes. A radiation intensity (i.e. a constant stream of particles or photons) gives rise to a continuous series of pulses; and if these are allowed to merge, they form a weak electric current, which may be amplified and registered by an electronic circuit. The final scale reading will then be a measure of the energy dissipated in the ionization chamber per unit of time by the ionizing particles or photons. This kind of detection instrument is thus a dose-rate meter (e.g. the so-called "cutie pie").

A small, electrically charged ionization chamber, held in place for instance by a finger ring, may be used to measure accumulated exposure dose. An electronic vacuum-tube voltmeter is often necessary to measure the charge reduction, which is proportional to dose.

2.1.3. Proportional counter

If the voltage difference between the anode and the wall of the counter is increased above a certain limit, another phenomenon, known as "secondary ionization", will become important. The electrons that have arisen from primary ionization will produce secondary ion pairs of the gas atoms in the counter tube, as they are accelerated towards the anode. This process of secondary ionization becomes increasingly important as the voltage difference between the electrodes is further increased. The final pulse size will be proportional to the energy of the initial ionizing particle (as long as all this energy is dissipated in the detector), provided the applied voltage remains constant during the measurement. Usually the radioactive sample will be placed inside the detector, which will be transfused by a gas at atmospheric pressure (gas-flow counters). In this way particles of low energy, such as the β^- from ^{14}C, may be counted effectively ("window-less" counting), provided suitable amplification precedes the register.

2.1.4. Geiger-Müller (G-M) counter

When the voltage difference between the electrodes of the detector is still further increased, secondary ionization becomes predominant and each primary ionizing event results in a discharge of a great number of electrons (avalanche). At this stage the large output pulse is independent of the energy of the initial particle or photon, and a further increase of the high voltage does not appreciably alter pulse size or count rate. Geiger-Müller counter detectors (G-M tubes) operate at this voltage "plateau". The discharges of secondary electrons initiated by one ionizing particle or photon would continue if the detector were of an open design, as in the gas-flow counter (atmospheric pressure). G-M tubes operate at a reduced gas pressure (about one-tenth atmosphere), containing a certain amount of "quenching" gas. Usually the closure of a G-M tube is a very thin mica window (1-3 mg/cm^2), and the filling gas is often a noble gas like argon with, for example, alcohol or halogen as the quenching gas. A certain number of molecules is dissociated during the quenching of each discharge with alcohol. Therefore, the quantity of quenching gas in the G-M tube decreases steadily, and consequently the life of the tube is limited by this effect. This disadvantage does not exist when a halogen gas, e.g. chlorine, is used for quenching, because the atoms of the dissociated chlorine molecule recombine; and the life of the tube is therefore determined by other effects, such as corrosion and leakage.

Energetic β^- or e-particles and γ- or X-photons emitted by radioactive liquids may be counted with a thin glass wall "dip-counter" G-M tube which is immersed in the liquid or with a specially designed liquid detector that consists of a cylindrical glass container around the G-M tube. The radioactive liquid thus surrounds the G-M tube in both

cases. Particles of low energy can obviously not be counted in this way because of absorption in the wall of the G-M tube.

The fact that some time is required for each discharge of electrons (100-300 μsec) implies that during this time no other particle or photon can be detected by the G-M tube. This time is called the dead time of the G-M counter; and, particularly for higher count rates, a correction for this dead time must be made.

Let $\mathscr{R}$ be the observed count rate and τ the dead time of the counter in min.

During one minute the counter will have been ineffective for $\mathscr{R}\tau$ min. Therefore, $\mathscr{R}$ counts have been registered in $1-\mathscr{R}\tau$ min. The corrected count rate $\mathscr{R}^+$ in cpm will therefore be

$$\mathscr{R}^+ = \mathscr{R}/(1 - \mathscr{R}\tau).$$

When the dead time of the counter tube is known, the correction for high count rates can then be made with the aid of the above expression for $\mathscr{R}^+$. However, this expression is approximate and should not be used to give corrections above 10%, when it is better to dilute or count at a distance from the detector.

Sometimes the dead time of a G-M tube will be fixed electronically at 300 or 400 μsec so that a correction table can be used. Correction is normally not necessary unless the count rate exceeds about 2000 cpm.

Numerical example:

τ = 300 μsec
= 5 μmin corr. = $2\frac{1}{2}$%
$\mathscr{R}$ = 5000 cpm
$\mathscr{R}^+$ = 5125 cpm

G-M counters are used most widely for the detection and measurement of β-particles. For γ-rays they are not very effective (1-3% efficiency); because most of the photons will penetrate the gas without any interaction. For the detection of β-particles on glassware, benches or trays, monitors are used. A monitor consists of a G-M tube connected to a power unit and a count-rate meter. Often a small loudspeaker is connected to the rate meter, so that a noise will warn the operator when the tube is in the vicinity of a contaminated spot.

Normally, for the assaying of activity in samples, the G-M tube will be connected to a voltage source, an amplifier, a register and a timing unit.

2.2. Detection by excitation

2.2.1. Solid scintillation counting

Solid scintillators are particularly suited for the detection of γ-rays and X-rays because of the high stopping power of the solid. Their operation is based on the following principle:

When a γ-photon interacts with a crystal, e.g. of thallium-activated NaI, at least one fast electron is liberated (see section 1.5.3.), and a constant fraction of the electron's kinetic energy is spent on excitation of orbital electrons in atoms of the crystal. On de-excitation these give rise to the emission of a light flash consisting of a number of photons. The number of light photons will be proportional to the energy dissipated in the crystal by the γ-photon.

The light photons reach the photocathode of a photomultiplier, where photoelectrons are released. The number of photoelectrons, being a constant fraction of the number of light photons, is therefore proportional to the energy originally dissipated by the γ-photon. The photocathode is connected with a series of dynodes, i.e. positive electrodes of increasing potential. When a photoelectron hits a dynode, secondary electrons are produced which will, in turn, hit the next dynode. In this way, the photomultiplier will, all in all, produce a large number of electrons (a pulse), proportional to the energy originally dissipated by the γ-photon in the crystal. This final pulse will be amplified linearly and registered.

As opposed to a G-M tube, the scintillation tube thus provides an output pulse that is proportional to the input energy. The scintillation tube is therefore a suitable detector for γ-ray spectrometry. A further advantage of the scintillation counter is its small dead time, of only a few μsec. This enables high count rates to be determined (up to at least 100 000 cpm) without the necessity for application of a correction for dead time.

For the measurement of β-particles, special plastic scintillators (as well as anthracene and naphthalene) which have a much higher efficiency than NaI crystals have been devised. An effective scintillator for alpha particles is a thin layer of silver-activated ZnS.

2.2.2. Liquid scintillation counting

For the counting of very-low-energy and low-energy beta particles such as ^{3}H (0.018 MeV) and ^{14}C (0.155 MeV), a method of detection called "liquid scintillation counting" is often employed. In this technique, the sample to be counted is placed in solution with the scintillator so that each radioactive atom or molecule is surrounded by molecules of the scintillator. By this method absorption is reduced, and hence counting yield increases.

The scintillator system contains a solvent which is usually an organic compound, such as toluene or dioxane, and a solute which is the actual scintillator. The solvent absorbs the energy and transfers it to the solute, which then emits the light flash. Often a secondary solute which acts as a wave-length shifter is added; i.e. it increases the wave length of the light flash emitted to one for which the photomultiplier tube is more sensitive, thus increasing the counting yield.

In practice, two photomultiplier tubes are often used facing each other across the counting chamber. A coincidence circuit is employed, and only those events witnessed by both tubes are counted. This increases the signal-to-noise ratio.

Variable discriminators can be applied to this system; and since the pulse height is proportional to the input energy, pulse-height analysis is possible.

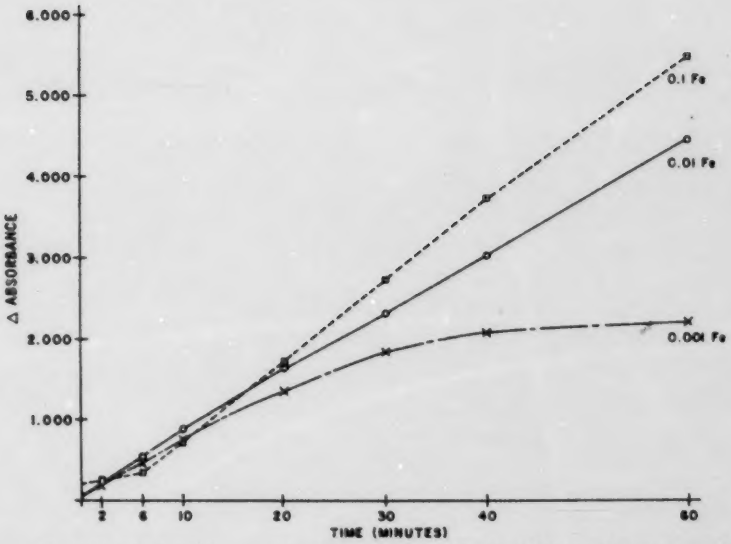

FIG. 11. Effect of initial ferrous ion concentration on linear portion of absorbance-irradiation time (dose) relationship. Dose rate approximately 60 krad/min

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2.3. Chemical dosimeters

Reactions employed in chemical dosimetry include (1) oxidation of ferrous salts to ferric, (2) reduction of ceric salts to cerous, (3) gas evolution from aqueous solutions (of iodides), (4) acid production in chlorinated hydrocarbons, (5) decolorization of methylene blue, (6) liberation of iodine from its compounds, and (7) changes in absorption, luminescence and other properties of solids such as glasses, plastics, etc.

Of these chemical dosimeters the one having some degree of general acceptance is the Fricke dosimeter. This dosimeter involves the radiation-induced oxidation of ferrous ions in an air-saturated 0.4 M sulphuric acid solution, to ferric ions. The oxidation is accomplished according to the following equations:

$$\text{Radiation} + H_2O = H + OH$$

$$Fe^{2+} + OH = Fe^{3+} + OH^-$$

$$H + O_2 = HO_2$$

$$Fe^{2+} + HO_2 = Fe^{3+} + HO_2^-$$

$$HO_2^- + H^+ = H_2O_2$$

$$Fe^{2+} + H_2O_2 = OH + OH^- + Fe^{3+}$$

The oxidation in appropriate ranges of radiation dose is proportional to the amount of radiation. The number of ferrous ions oxidized per 100 eV of energy absorbed, designated as the G value, is 15.5.

The Fricke method has been adopted as the standard test method for absorbed gamma radiation dose by the American Society for Testing Materials (ASTM Designation: D1671-63).

The ferrous sulphate-cupric sulphate dosimeter is a modification of the Fricke ferrous sulphate dosimeter. The G value of 15.5 limits the Fricke dosimeter to a dose range of 2 to 40 krad. Adding cupric sulphate to the Fricke dosimeter reduces G (Fe^{3+}) to 0.66. The ferrous sulphate-cupric sulphate dosimeter has a range of 10 to 800 krad. This range is obtained when the dosimeter solution is an air-saturated solution containing 0.001 M $FeSO_4$, 0.010 M $CuSO_4$ and 0.01 N H_2SO_4. The range can be extended to above 3000 krad by modifying the solution so that the ferrous ion concentration is 0.01 M. This is shown by the data in Fig.11.

The reactions of the ferrous sulphate-cupric sulphate dosimeter are as follows:

$$Fe^{2+} + OH = Fe^{3+} + OH^-$$

$$H + O_2 = HO_2$$

$$Cu^{2+} + H\,(e^-aq.) = Cu^+ + H^+$$

$$Cu^{2+} + HO_2 = Cu^+ + H^+ + O_2$$

$$Fe^{3+} + Cu^+ = Fe^{2+} + Cu^{2+}$$

$$2\,Fe^{2+} + H_2O_2 = 2\,Fe^{3+} + 2\,OH^-$$

There is no dose-rate effect, since all but the last reaction are fast. This reaction has a half period of 14 sec. Since oxygen is not consumed, the G (Fe^{3+}) value is not affected.

2.4. Film dosimeters

The need for simple, ready-made dosimeters, suited for routine use has lead to the development of a number of plastic film systems. In most cases, commercially available plastic films or sheets have been tested empirically and the more promising systems have then been investigated in more detail and improved. Examples of such films for routine dosimetry are the red Perspex[1] and clear polymethylmethacrylate[2].

Such systems have proved to be extremely useful for dose distribution measurements and for process monitoring. Careful calibration must

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[1] WHITTAKER, B., Gamma Radiation Dosimetry in the Dose Range 10^5 - 5×10^6 rads using Commercial Red Perspex, UKAEA Rep. R. 3360 (1963).

[2] BROOKHAVEN NATIONAL LABORATORY, Evaluation of Perspex-HX as a Gamma Ray Dosimetry Material, Brookhaven, N.Y., USA, Rep.11 (1967) 192.

be carried out for each production batch of such plastic films, often even for each sheet of material. This calibration can be done by checking against the Fricke dosimeter, which is always used as the standard.

3. HEALTH PHYSICS

3.1. Units: Basic considerations

A health hazard is involved when human tissues are subjected to ionizing radiation. The nature and the degree of the damage that is caused depend on the degree to which the particular radiation is able to penetrate the tissues, its specific ionization, i.e. whether a small or a great number of ion pairs are produced per unit length of track, and the type of tissue being irradiated.

Usually radiation tissue damage will increase with the degree of cell reproduction and decrease with the degree of differentiation.

A commonly used unit of electromagnetic radiation is the röntgen (R), which is essentially defined as that dose of γ- or X-radiation which produces ion pairs carrying 1 electrostatic unit (esu) of charge (of each sign) per cm^3 of standard air surrounded by air. As the numerical charge of an electron is 4.8×10^{-10} esu, $1/(4.8 \times 10^{-10}) \doteq 2.1 \times 10^9$ ion pairs per cm^3 are formed during the penetration of air by 1 R.

For the formation of one ion pair in air, about 33 eV is required on the average. One röntgen will therefore be equivalent to $2.1 \times 10^9 \times 33$ eV = 6.9×10^4 MeV = 0.11 erg of radiation energy absorbed per cm^3 of air.

As 1 cm^3 air has a weight of 0.0013 g, one röntgen will dissipate 0.11/0.0013 = 85 erg/g air.

A unit of absorbed dose is the rad, one rad being equal to an absorbed dose of 100 erg/g of irradiated material. The rad-dosage absorbed during the exposure of a material to a given dose (e.g. 1 R) of radiation is different for different materials, depending primarily on the scattering power (electron density) of the constituent atoms.

The rad unit as such is independent of the nature of the radiation.

It is obvious, however, that radiation dissipating 1 rad with a high specific ionization will have a greater biological effect than will radiation dissipating 1 rad with a low specific ionization. For combination of the biological effect of various kinds of radiation, a standard of comparison, X-rays of 200 keV, has been adopted. Based on comparison with the standard, a concept has been defined: the RBE (relative biological effectiveness).

$$\text{RBE} = \frac{\text{dose in rad from 200 keV X-rays causing a specific effect}}{\text{dose in rad from radiation causing the same effect}}$$

RBE values, as they stand today, are given in Table II.

For a combination of the effect of doses of different kinds of radiation, the rad and the RBE have been combined. The product of RBE and the dose in rad units is called the dose in rem units (röntgen equivalent mammal or man).

TABLE II. VALUES OF RELATIVE BIOLOGICAL EFFECTIVENESS

RBE	Kind of radiation
1	X, γ, β
10	fast neutrons
3-4	slow neutrons
10	α
20	nuclear fragments

TABLE III. K_{γ} VALUES AT VARIOUS γ-PHOTON ENERGIES

	Approx. K_{γ}-value (R/h at 1 m from 1 Ci)	Predominant γ-photon energy (MeV)
^{22}Na	1.2	1.3 and 0.5[a]
^{24}Na	2	2.8 and 1.4
^{28}Mg	1.6	1.8 and 1.4
(+ equil. ^{28}Al)		
^{42}K	0.15	1.5
^{51}Cr	0.02	0.3
^{54}Mn	0.5	0.8
^{58}Co	0.6	0.8 and 0.5[a]
^{59}Fe	0.6	1.3 and 1.1
^{60}Co	1.3	1.3 and 1.2
^{64}Cu	0.1	0.5[a]
^{65}Zn	0.3	1.1
^{82}Br	1.5	1.5 - 0.6
^{86}Rb	0.05	1.1
^{95}Zr	0.4	0.8 and 0.7
^{131}I	0.2	0.4
^{137}Cs	0.3	0.7
(+ equil. ^{137m}Ba)		
^{182}Ta	0.7	1.2 and 0.2
^{198}Au	0.3	0.4
^{226}Ra		
(+ equil. decay chain) with 0.5-mm Pt cover	0.825	many different

[a] Annihilation photons following β^+

Dose in rem = (Dose in rad) × RBE

1 rem of β-radiation will per definition have the same biological effectiveness as 1 rem of γ- or neutron radiation. Therefore, doses expressed in rem units may be added in evaluation of the sum effect of a mixture of different kinds of radiation.

It is of importance that, before beginning any work with appreciable amounts of radioisotopes, the operator should know how great the electromagnetic radiation intensity from the source will be. Before the use of a dose-rate meter, which gives the number of röntgen per unit of time, the dose rate at a particular distance from the source in question should be estimated from the K_γ^*-value when the nature of the radioisotope is known (see Table III).

A "point" source of C^* curies of an isotope, which emits on the average a γ-ray energy of $\bar{E}$ MeV per disintegration, will generate an energy flux of

$$(3.7 \times 10^{10} \times C^* \times \bar{E})/4\pi d^2 \text{ MeV/sec per cm}^2$$

at d cm from the source. If μ is the absorption coefficient per cm of air, $(3.7 \times 10^{10} \times C^* \times \bar{E} \times \mu)/4\pi d^2$ MeV/sec will be absorbed per cm^3 of air (at d cm from the source). As 1 röntgen is equivalent to 6.9×10^4 MeV absorbed per cm^3 of air (see fourth paragraph in this section), the dose rate at d cm will be $(3.7 \times 10^{10} \times C^* \times \bar{E} \times \mu)/(4\pi d^2 \times 6.9 \times 10^4)$ R/sec or about $1.5 \times 10^5 \times (C^* \times \bar{E} \times \mu)/d^2$ R/h.

The above equation can be simplified when C^* is taken as 1 Ci, d as 100 cm (1 m), and the fraction, μ, of γ-photons absorbed per cm^3 of air as about 33×10^{-6} for all photon energies in the range 0.1 - 3 MeV. Then the specific dose rate, for γ-energies in the range 0.1 - 3 MeV, is $K_\gamma^* \doteq \frac{1}{2}\bar{E}$ R/h at 1 m from 1 Ci "point" source. $\bar{E}$ may be evaluated for a particular radioisotope by a study of the energies of the photons and the branching ratios in the decay scheme of that isotope. Table III lists K_γ^*-values, together with the predominant γ-photon energies.

3.2. Radiation hazard

Two kinds of hazard may be distinguished:

(1) External irradiation from a source outside the body, and

(2) Internal irradiation from isotopes which have entered the body.

With regard to total body irradiation (external plus internal), the International Commission on Radiological Protection (ICRP) has fixed the accumulated dose that may be received by occupational workers.

The maximum permissible accumulated total body dose up to age N is $D = 5(N-18)$, in which D = accumulated doses of radiation expressed in rem, and N is the age of the person in years.

Based on the above criteria, it is advisable that the average yearly dose to be received by a worker should not exceed 5 rem, and the average weekly dose should remain below 0.1 rem. The accumulated dose over any consecutive 13 weeks shall be less than 3 rem. These criteria pertain to exposure of the gonads or blood-forming organs as well as to total body radiation.

When only hands are subjected to radiation, the maximum permissible levels are higher and amount to 20 rem per 13 weeks or 75 rem per year.

This means that for work with β- and γ-emitters which have an RBE value of 1 the maximum permissible average dose for the entire body, the blood-forming organs or the gonads should not exceed 0.1 rad per week. When only hands are subjected to radiation, 1.5 rad per week is the maximum permissible average dose.

1 R of penetrating γ-radiation (above 0.2 MeV) will dissipate about 1 rad in body tissue. X- or γ-photons of energy below 0.1 MeV will dissipate 2 - 5 rad per röntgen in bone tissue. α- and β-emitters become hazardous on entry into the body. The calculation of the number of rad in such a case can be a difficult and complex task.

The hazard involved when radioisotopes are ingested or inhaled will depend on a number of factors, such as

(1) Half-life and energy of the isotope;
(2) Biological half-life, i.e. the time required for the elimination of half of the ingested material from the human body;
(3) The accumulation of isotopes in critical organs; and
(4) Formation of toxic by-products as a result of (a) splitting of molecules by radiation or (b) reactions of free radicals.

A number of isotopes and a classification of their danger when ingested by the human body are listed in Table IV. The highly toxic elements such as ^{90}Sr, ^{45}Ca and ^{89}Sr accumulate in bones and produce damage to the blood-producing cells. ^{131}I accumulates in the thyroid gland. The moderately toxic elements do not accumulate to such high degrees in critical organs and have a relatively short biological half-life. Tritium and ^{14}C are usually only slightly toxic because of their rapid biological turnover. However, ^{3}H and ^{14}C can be very toxic under conditions of slow turnover (e.g. in nucleic acids) or, for example, as $Ba^{14}CO_3$ dust lodged in the lungs.

Normally work in the area of food irradiation does not involve hazards associated with the ingestion of isotopes.

3.3. Safety procedures and precautions

Protection against external radiation is obtained by three different means:

(a) distance,
(b) short exposure time,
(c) shielding.

When working with radioisotopes in the laboratory, it is possible to use distance and short exposure time under certain circumstances as safety precautions. The possibility of using these depends on the type of the source material and the dose rate. In the case of food irradiation research, where ^{60}Co or ^{137}Cs are involved, the source energy and number of curies involved makes it absolutely necessary to depend on shielding as the safety factor against exposure to ionizing radiation.

Any person dealing with, or working in the vicinity of radioactive isotopes should wear a film badge on the wrist and/or on the laboratory coat. The blackening produced on development of the film is a measure

TABLE IV. DANGER OF ISOTOPES INGESTED BY THE HUMAN BODY

	Isotope
Very highly toxic	^{90}Sr
Highly toxic	^{45}Ca, ^{89}Sr, ^{140}Ba, ^{131}I
Moderately toxic	^{22}Na, ^{24}Na, ^{32}P, ^{35}S, ^{36}Cl, ^{42}K, ^{52}Mn, ^{54}Mn, ^{56}Mn, ^{55}Fe ^{58}Co, ^{60}Co, ^{64}Co, ^{65}Zn, ^{82}Br, ^{86}Rb, ^{99}Mo, ^{137}Cs, ^{137}Ba
Slightly toxic	^{3}H, ^{14}C

of the external dose of radiation that has been received during the exposure time. Control films have to be calibrated by means of a standard radiation source and developed together with the film badge. Various types of film badge, which permit separate evaluation of the accumulated dose received from β- or γ-rays, or neutrons have been designed.

Besides a film badge, and especially in the absence of a film-badge service, a pocket dosimeter should be used.

3.3.1. Shielding against radiation

The irradiation of food in the laboratory is generally carried out in a radiation source that is "self-shielding". In this case, the source material (^{60}Co) is contained in a cask, having a lead shield surrounding it, and the food sample material to be irradiated is inserted in a "drawer" and brought into the presence of the radiation field. This is done by manipulation in such a way that at no time does the irradiation escape from the irradiator into the space occupied by the worker.

In certain cases, a small room is made available for irradiation, by properly shielding it, and the irradiation source material is stored in a safe position, i.e. under water or beneath a lead plug. The source is manipulated remotely, so that samples left in the room will be irradiated when the source is brought from the "safe" storage position into the irradiating position. By means of safety locking devices, the room can be secured so that it can be entered by the worker only when the source is in the safe position.

In each of these cases, the adequacy of the shielding is very important, since the workers must be adequately protected against the irradiation at all times. Any radiation source used in food irradiation work must naturally comply with all the safety regulations covering industrial installations and must be safe from a radiation standpoint.

Annual dose limits of radiation to various categories of persons have been set and agreed upon internationally. These annual limits, however, can be converted for design purposes into dose rate. These are:

General public: $\simeq$ 0.06 mR/h (corresponding to 0.5 rem/year)
Radiation workers: 2.5 mR/h (during working hours - 40 h/week)

TABLE V. THICKNESS IN CENTIMETRES TO DECREASE THE RADIATION DOSE RATE BY VARIOUS FACTORS

Shield material \ Attenuation factor	10	10^3	10^4
Lead (density 10.8)	5	13.3	25.4
Iron (density 7.8)	9.2	22.8	41.6
Heavy concrete (density 3.4)	20	51	92
Ordinary concrete (density 2.3)	32	75	135
Water (density 1.0)	70	145	850

Classified workers are those whose accumulated radiation dose may be measured weekly by film-badges, such as for workers in nuclear centres. Most plants are built for the limit of 0.75 mR/h. In order to bring about this necessary reduction in dose level, the radiation must be absorbed in shielding material, such as concrete or lead. Standard density concrete (2.3 g/cm^3) is generally used for construction walls and roofing of room facilities and lead for mobile facilities.

Table V gives the thickness of various materials required to decrease the dose rate for a ^{60}Co source by factors of 10, 10^3 and 10^6. This table can be used as a guide in estimating the amount of shielding necessary when planning the construction of a radiation facility.

4. RADIATION CHEMISTRY

4.1. Fundamentals

Two basic processes occur when a proton or a particle of ionizing radiation acts upon matter. The primary process causes the formation of ions, excited molecules or molecular fragments. The secondary process involves the interaction of products of the primary process, and can lead to the formation of compound different from those initially present. The primary process is independent of the temperature, whereas, the secondary process is dependent upon temperature and other variables (e.g. for gases, pressure).

As an example of these two processes, consider the irradiation of molecular gaseous hydrogen with alpha particles.

Primary process:

$$H_2 + \alpha = H_2^{*} + 2\,H$$

$$H_2 + \alpha = H_2^{+} + e^{-}$$

* indicates excited state in this case.

Secondary process:

$$H_2^+ + H_2 = H_3^+ + H$$

$$H_3^+ + e^- = H_2 + H$$

$$H_3^+ + e^- = 3\,H$$

It has been noted (see section 1.5.) that the interaction of ionizing radiation with matter is complex. None the less, the resultant effect at the molecular level for both electromagnetic and corpuscular radiation is as given above, if the limits of energy are below 10 MeV. Above this value, nuclear transformations leading in some cases to induced radioactivity, also become probable.

Although the incident ionizing radiation may be monoenergetic, the actual radiation within the absorbing medium encompasses a wide range of energies. As the incident radiation proceeds into the medium, it is dissipated, primarily by interaction with electrons. A sufficiently energetic interaction can lead to the ejection of an electron from an atom or molecule and cause ion formation. A less energetic collision may cause only the transfer of energy to the atom or molecule to cause excitation. By repetition of these processes, a degradation of the energy of the incident radiation occurs. In this way, along the path of the radiation, there exists a range of energies. Some of these different energy levels are associated directly with the primary radiation, some are those related to secondary radiation produced by interaction of the primary radiation with the absorber.

It is to be noted that only absorbed radiation can accomplish change. The "G" value is the number of molecules reacting or produced per 100 eV of absorbed energy. The number of reacting molecules per unit of radiation can vary greatly. Many activated molecules lose their energy before a chance for reaction occurs and in this way, cause some inefficiency of the process. In some cases, an exothermic reaction occurs, causing excitation of additional molecules and leading to additional reactions. Chain reaction also can be initiated; in this way, a small amount of radiation can cause substantial change.

4.2. Reactions relating to non-foods

Irradiation of gaseous 0_2 can lead to ozone formation. Mixtures of nitrogen and oxygen form nitrogen oxides, which in the presence of water form nitric acid. Ozone is also formed. These reactions may have meaning for the irradiation of certain foods in the presence of air or oxygen, since ozone and nitrogen oxides can cause changes in foods through chemical action.

One of the most interesting and important substances which undergo change when irradiated is water. Despite extensive investigations, the complete understanding of what happens has not been obtained. The final products of the irradiation of water are only hydrogen and hydrogen peroxide, but it is known that the mechanism whereby these are formed is complex.

It is believed that three kinds of intermediate reactive products are formed: (1) the hydrated electron ($e_{aq.}$), (2) the hydroxyl radical ($OH\cdot$) and (3) hydrogen atoms ($H\cdot$). These products are capable of reacting in different ways. The hydrated electron is a reducing agent, the hydroxyl radical is an oxidizing agent. The hydrogen atom can act either as a reducing or oxidizing agent. These free radicals can react in a number of ways, such as:

$$(e_{aq.}) + H_2O = H\cdot + OH\cdot$$

$$H\cdot + (OH\cdot) = H_2O$$

$$H\cdot + H\cdot = H_2$$

$$(OH\cdot) + (OH\cdot) = H_2O_2$$

$$H\cdot + H_2O_2 = H_2O + (OH\cdot)$$

$$(OH\cdot) + H_2O_2 = H_2O + HO_2\cdot$$

$$H_2 + (OH\cdot) = H_2O + H\cdot$$

$$H\cdot + O_2 = HO_2\cdot$$

$$HO_2\cdot + HO_2\cdot = H_2O_2 + O_2$$

As might be expected, the conditions under which the irradiation is conducted affect the results. Temperature, pH value and purity of water can be of influence.

While the end products, H_2 and H_2O_2 are of interest, the intermediate ones also can be of importance. Two points are especially noteworthy: (1) while transient, these intermediates do exist for a finite period and (2) in at least some of the possible physical states of water, the active molecular fragments can move and in this fashion contact other molecules with which they can react. For aqueous solutions, or for materials containing water, such as foods, these highly reactive products of the radiolysis of water can produce an indirect effect of the radiation with the substances dissolved in the water.

Because the products of the radiolysis of water include substances which are either oxidants or reducing agents, it is clear that both oxidations and reductions can occur upon the irradiation of water. The Fricke dosimeter discussed previously (see section 2.3.) is an example of an oxidation induced by radiation.

The radiolysis of organic compounds also can be complex. A number of primary processes occur leading to excitation, ionization and dissociation. The possibilities of secondary effects from the interaction of these products can be manifold, depending upon the chemical nature of the original material and the conditions of irradiation. There may be a pattern of somewhat random splitting of the chemical bonds present, as occurs, for example, with saturated hydrocarbons. On the other hand, certain bonds are more readily broken than others. As a consequence, it is impossible to predict the exact outcome of the irradiation of a particular

compound or of a mixture of compounds. One can find fragments of lower molecular weight than the original substance, polymers, products of the interaction of radiation-produced intermediates with each other or with parent substances, altered parent substances (e. g. dehydrogenation, de-carboxylation, de-amination, etc.), and new compounds formed by interaction of two or more starting substances (e. g. the formation of benzene hexachloride from Cl_2 and benzene). Exothermic reactions or chain reactions in some cases produce high efficiencies in the use of radiation to produce changes.

While the complexity of the radiation-induced reactions makes prediction of the course of a particular reaction difficult, control of conditions does lead to consistent results, and useful applications of radiation exist. Cross-linking of polyethylene, for example, to raise the melting point of this material is carried out commercially.

4. 3. Reactions relating to foods

In this section, consideration will be given to the action of radiation on important components of foods.

4. 3. 1. Amino acids and proteins

The study of amino acids can provide information helpful in understanding changes in the very much more complex protein molecules. The principal action on amino acids in aqueous solution is deamination, leading to the formation of ammonia and in some amino acids, to aldehyde residues. Amino acids containing sulphhydryl groups undergo oxidation of the sulphur to produce hydrogen sulphide. Cysteine, containing -SH group forms disulphide cystine. Those with a ring structure can undergo rupture of the ring. Studies of certain specific amino acids have revealed the formation of other products such as fatty and other acids, amines and carbon dioxide. The indirect effect of radiation increases with decreasing concentration as shown by the data of Fig. 12 relating to the decomposition of DL-phenylalanine in water by electrons.

Irradiation of amino acids in the dry state can lead to the formation of free radicals whose presence can be demonstrated by electron spin resonance for extended periods of time.

A protein molecule responds to radiation in a dual fashion, as a protein entity and as individual amino acids and other constituents. The generalized phenomenon of denaturation manifests itself in the changes commonly associated with this protein alternation, namely, changes in viscosity of solutions, in solubility, in electrophoretic behaviour, in changes in absorption spectra, in reaction with enzymes, in exposure of -SH groups and in immunological changes. Splitting of protein molecules into smaller units can occur. Aggregation has also been noted, and both fragmentation and aggregation have been found to occur simultaneously.

Energy absorbed by a protein molecule can be translocated to a more "sensitive" site where an initially broken bond can lead to specific chemical changes such as were indicated for isolated amino acids. In proteins containing sulphur, the sensitive location is at the sulphur linkage. Different sensitivities to the radiation can exist in a protein molecule giving rise to a preferred and consistent response.

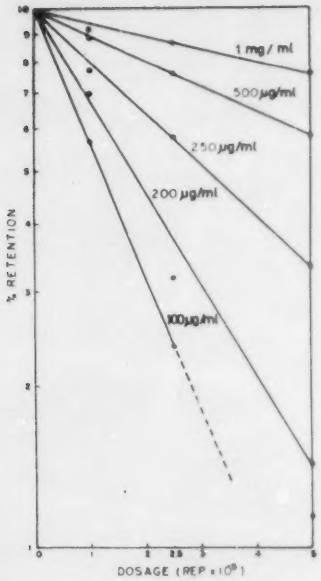

FIG. 12. Decomposition of DL-phenylalanine by high voltage cathode rays

All these effects result from a combination of the primary (direct) and secondary (indirect) processes referred to in section 4.1. The relative importance of each kind of effect will vary depending upon many factors, such as concentration, availability of oxygen, temperature, nature of the protein, the presence of other substances, etc.

Irradiation of dry proteins, however, involves almost entirely the primary or direct effect. As with amino acids, free radicals formed from a variety of moieties of the protein molecule have been observed.

4.3.2. Enzymes

Enzymes are important constituents of living tissue and since many foods are either living organisms (e.g. fresh fruits) or are closely derived from such (e.g. fresh meat), enzymes are frequently constituents of the foods. There are a great many enzymes and all are proteins. Since they are proteins, it is to be expected that the action of radiation on enzymes will be no different from that on other proteins. Enzymes, however, exhibit certain specific functional characteristics which frequently are of interest in connection with a food and changes in these characteristics, or sometimes, a failure to respond to radiation can be a matter of special concern. The enzyme activity is usually a sensitive and convenient index of change, making it possible to detect the action of radiation on these proteins more easily than may be the case for some other proteins.

As is to be expected, the circumstances under which the enzyme exists have a great influence on the changes induced by radiation. Inactivation

TABLE VI. ELECTRON INACTIVATION OF PEPSIN IN AQUEOUS SOLUTION

mg pepsin/ml	krad to produce 63% inactivation
0.5	136
1.0	260
2.0	523

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appears to come about through denaturation, but other more specific changes can also occur. Dilute pure aqueous solutions of enzymes are sensitive to radiation. Increasing the concentration requires more radiaction to produce the same inactivation, as may be seen from the data of Table VI.

The inclusion of other substances in the enzyme solution also decreases the sensitivity of the enzyme to radiation. Figure 13 gives data showing the protective action of sodium D-isoascorbate on pepsin in acetate buffer solution. The radiation sensitivity of enzymes in aqueous solution increases with temperature, as shown for pepsin in Fig. 14.

Other factors affect the sensitivity of enzymes to radiation. Enzymes that are dependent upon the presence of an -SH group for activity are especially sensitive. The pH value of the solution, or its oxygen content, is an important factor for some enzymes. Inactivation of dry enzymes requires greater amounts of radiation than for aqueous solutions.

The sensitivity of enzymes to radiation is, therefore, not simply stated. Details of the environment of the enzyme must be known and generally it can be expected that the more complex this environment is, the less sensitive to radiation will be the enzyme. In the usual complex food systems, enzymes are well protected and the radiation requirements for inactivation are quite large.

4.3.3. Carbohydrates

The simple sugars such as glucose, when in dilute aqueous solution, respond to radiation primarily through the secondary or indirect effect. Monosaccharides undergo oxidation and fragmentation, the exact product depending upon the nature of the sugar. Glucose, for example, yields glucuronic acid, gluconic acid, saccharic acid, glyoxal, arabinose, erythrose, formaldehyde and dihydroxyacetone. Oligosaccharides form monosaccharides and products similar to those obtained with the irradiation of the simple sugars. Irradiation of polysaccharides such as starch and cellulose causes degradation into smaller units such as glucose, maltose, dextrins along with the products of irradiation of these substances. Pectin, a mixture of several carbohydrates, found in plant tissue is also depolymerized. Glycogen, an animal tissue polysaccharide, is also broken into smaller units by radiation.

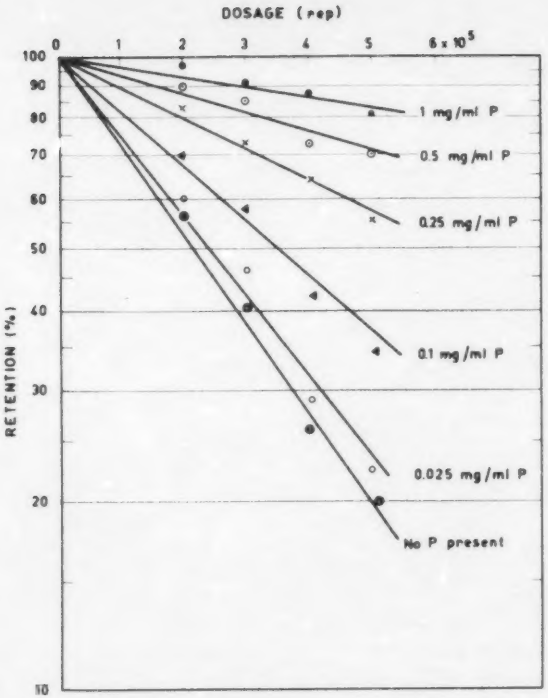

FIG. 13. Effects of cathode rays on pepsin (1.0 mg per ml) in acetate buffer (pH 4.3) in the presence of different amounts of sodium D-isoascorbate (P is protector)

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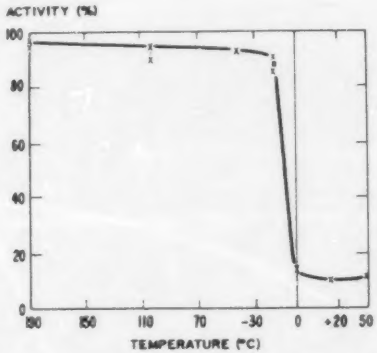

FIG. 14. Effect of temperature on the inactivation of 10 mg per ml solution of pepsin by 2.325 Mrad

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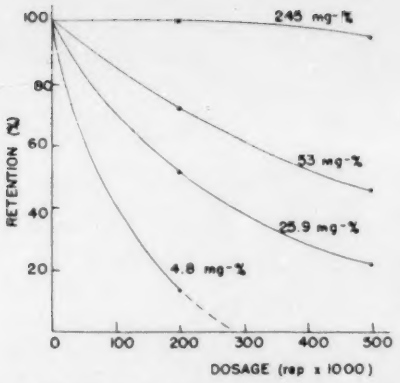

FIG. 15. The effect of 3-MeV cathode rays on different concentrations of l-ascorbic acid

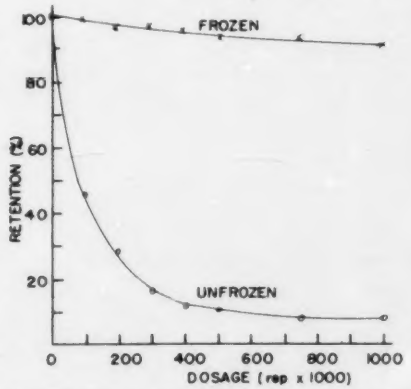

FIG. 16. The effect of 3-MeV cathode rays on frozen and unfrozen solutions of l-ascorbic acid (8.0 mg%) in 0.25% oxalic acid

4.3.4. Lipids

The principal action of radiation on lipids involves direct cleavage of C-C bonds in the long chains of the fatty acids. This leads to formation of normal alkanes. Secondary reactions lead to the formation of normal alkenes. In the presence of oxygen, an alkyl-free radical can react to form a peroxide which can go on to form a hydroperoxide. This process is probably very similar to the normal autoxidation of fats leading to aldehyde and ketone formation. The proportion of the carbonyl compounds formed is considerably less than that of the alkanes and alkenes.

4.3.5. Vitamins

Vitamins are important micronutrients in foods. Many food preservation processes cause some vitamin loss and the effect of irradiation on these substances is a reasonable matter of interest. The structures of

most vitamins are known. Vitamins can usually be obtained in pure forms, often synthetically produced. As would be expected, the effect of radiation on a vitamin is greatly dependent upon the environment in which the vitamin exists. Simple systems such as a pure water solution, especially if dilute, show a large effect of radiation. More complex environments such as exist in foods lead to a reduced sensitivity to radiation.

Vitamins can be classified as to whether they are water or fat soluble. The widely varying chemical structures of vitamins result in differences in response to radiation. Of the water soluble vitamins, vitamin C or ascorbic acid is the most sensitive, resulting in the formation of dehydroascorbic acid and other products. Vitamin C readily reacts with the free radicals of water radiolysis and can be used as an agent for reducing certain indirect effects of radiation related to these free radicals (e. g. flavour changes). The effect of varying concentration in water is shown in Fig. 15.

Figure 16 shows the effect of freezing on the retention of ascorbic acid in an aqueous solution. Both of these demonstrate the indirect effect of the radiation on the destruction of this vitamin. The vitamins known as the vitamins of the B complex are also water soluble. Of these, thiamin, riboflavin, pantothenic acid, pyridoxine and folic acid are radiation sensitive. Niacin is quite insensitive. As with vitamin C, the radiation sensitivity is related to the environment and is greater in simpler systems.

The fat-soluble vitamins include vitamin A, D, E, and K. All are radiation sensitive, especially E and K. As with the water soluble vitamins, the environment is important.

5. EFFECTS OF RADIATION ON LIVING ORGANISMS

5.1. Fundamental concepts

It is presumed that the biological effects of radiation are due to chemical changes within the organism. As with other materials the effects of radiation on living organisms can be divided into direct and indirect effects. The presence of substantial quantities of water is normal in living tissue. Consequently the indirect effect of radiation normally occurs as an important part of the total action of radiation. Drying or freezing of the tissue can reduce or remove this mechanism.

No specific toxin produced by radiation has been demonstrated, however, abnormal metabolic products with toxic properties may sometimes appear in tissues after irradiation.

The effect of radiation on a living organism requires a certain time for its manifestation. The sequence of events following irradiation can occur in different ways depending upon the dose. Radiation damage is mainly associated with the impairment of metabolic reactions. An important aspect of the reaction of living organisms to radiation is the capability of the organism to recover from radiation injury. This capability is related to many factors, perhaps the most important of which is total dose. A sufficiently high dose can prevent recovery.

The effects of radiation cannot be simply described for all organisms, since these effects are related to the nature of the organism and especially to its complexity. The correlation of radiation sensitivity is roughly

TABLE VII. APPROXIMATE DOSE (rads) TO KILL VARIOUS ORGANISMS

Organism	Dose
Higher animals, including mammals	500 - 1000
Insects	1000 - 100 000
Non-sporulating bacteria	50 000 - 1 000 000
Sporulating bacteria	1 000 000 - 5 000 000
Viruses	1 000 000 - 20 000 000

inversely proportional to size. The viruses, the most minute living entities, are most radiation resistant, some surviving as many as 10 000 000 rad. Man, approximately at the other end of size range and complexity, suffers death with only 500 rad. Effects on other types of organisms fall within these limits as shown in Table VII.

Since all living organisms (except viruses) contain one or more cells, as the basic unit, the effect of radiation on cells has been studied extensively. Effects which have been detected include changes in shape and structure, alteration of metabolic reactions, alteration of reproduction, including mutations, altered nutrient requirements, and death. Cells in an active metabolic state are more sensitive to radiation than those in a dormant or resting condition.

The consequence of radiation damage to a cell will vary with nature of the organism. Compared with multi-cell organisms, single cell organisms are more vulnerable to the consequences of radiation damage, since the cell is the whole organism. Damage to some of the cells of a multi-cell organism does not necessarily have a serious consequence for the total organism. On the other hand, the complexity of a multi-cell organism can make certain kinds of damage critical in its functioning. This in part explains the inverse relation between lethal dose and complexity of the organism.

For doses less than lethal the effects of radiation will vary depending upon the timing of the irradiation with respect to the stage of development of the organism. Application, for example, during the growth stage can affect the maturation of the organism and could include alteration of the normal structure, metabolism, reproduction etc.

5.2. Actions on organisms relating to foods

Living organisms are associated with foods in various ways. Some foods, such as fruits and vegetables, are themselves living organisms. The effects of radiation on these can have significance and utility in the various steps of handling foods between harvest and consumption.

The presence of a living organism in a food can affect the acceptability of that food. The significance of the presence of the organism can vary from a true health hazard to objection on the basis of aesthetic or spoilage changes of a sensory character. The significance of a particular organism depends upon many factors, most important of which is the

nature of the organism. From the standpoint of the irradiation of foods, the following kinds of organisms have importance:

Viruses and Rickettsia	Moulds
Bacteria	Helminths
Yeasts	Insects

5.2.1. Viruses

Viruses are the smallest living entities. They are dissimilar from true organisms in that they have no respiration and are dependent upon a host for food and enzymes. They are capable of reproduction and can affect their host. They can infect both plants (including bacteria) and animals. The principal concern with respect to irradiation of foods is to inactivate viruses present which have a health or economic significance. Heating is a very effective agent for the inactivation of viruses and foods which are normally cooked either during processing or in preparation for the table usually are not cause for concern. The only exception to this is the chance of post-preparation contamination of a food by a food handler.

Foods have been incriminated in the transmission to humans of the viruses of poliomyelitis and infectious hepatitis. The poliomyelitis virus contamination has been presumed to be the consequence of a human carrier handling the food. The contamination of food with virus of infectious hepatitis has been ascribed to the same cause or, and in the case of shellfish, due to contamination from polluted waters from which they were taken.

A major problem, largely of economic significance, is the contamination of raw meat with the virus of the foot and mouth disease. Ordinarily, this virus does not infect humans, but does attack many animals, including the usual domesticated meat animals. The disease exists in widespread areas of the world, only North America, Australia and New Zealand being free of it. The disease-free countries prohibit the importation of raw meat from those areas in which the disease exists, because of the dangers of transmitting the disease to the animals of the importing country.

Other similar animal viral diseases exist, including Rinderpest and Swine Fever.

Radiation can inactivate viruses only at high doses. Three Mrad has been shown to inactivate foot and mouth disease virus suspended in an aqueous medium. For inactivation in the dry state, 4 Mrad were required. Most of the doses demonstrated to be effective in raw products, would produce undesirable effects on the food. There is little problem in products that have been heated to 60 - 70°C for a short period of time, as such temperatures inactivate the virus.

5.2.2. Bacteria

Bacteria generally are present in all foods except those processed to destroy a natural contamination. Control of spoilage of food usually involves control of bacterial action. Certain bacteria, which can be carried by foods are pathogenic to man. The nature of the food, its treatment and the storage conditions affect the bacterial pattern.

There are a large number of kinds of bacteria differing in morphological and physiological characteristics. An important classification

TABLE VIII. D_{10} VALUES OF SELECTED BACTERIA

Bacterium	Irradiation medium	D_{10} (krad)
Ps. aeruginosa	Nutrient broth	3
Ps. fluorescens	Nutrient broth	2
Ps. geniculata	Nutrient broth	5
E. coli	Nutrient broth	10 - 20
S. aureus	Nutrient broth	10
S. aureus	Dry	65
S. senftenberg	Meat-and-bone meal	50
S. senftenberg	Liquid whole egg	17
S. senftenberg	Dried egg	45 - 60
S. typhimurium	Meat-and-bone meal	60
M. radiodurans	Raw beef	250
	Raw fish	339
B. subtilis (spores)	Saline	260
B. subtilis (spores)	Pea puree	35
C. botulinum (spores)		
Type A 12885	Phosphate buffer	241
	Canned chicken	311
	Canned bacon	189
Type B53	Phosphate buffer	329
	Canned chicken	369
	Canned bacon	204
C. sporogenes (PA 3679/52)	Phosphate buffer	209
C. perfringens	Aqueous suspension	120 - 200

basis is grouping as to spore-formers or non-spore-formers. Both groups can exist as vegetative forms, but certain ones undergo change under proper conditions to form spores. Spores are more resistant to stress conditions than vegetative cells. Under proper conditions, spores can germinate and grow as the vegetative form.

From the standpoint of foods, concern about bacteria involves the following: (a) Bacteria can cause sensory and other changes frequently considered undesirable and usually associated with spoilage.

(b) Certain organisms growing in a food produce a toxin, harmful to man.

(c) Certain organisms in food can infect man and animals and thereby cause a disease condition

Many food preservation measures are directed toward control or destruction of spoilage microorganisms. Radiation is capable of destroying microorganisms and consequently is an applicable preservation agent. As would be anticipated, radiation acts through direct and indirect action, since water is generally a component. The action of radiation on bacteria is influenced by the following: amount of radiation, species and strain of

bacteria, concentration or numbers of bacteria, chemical composition of medium, physical state of medium, post-irradiation storage conditions.

The sensitivity of an organism to radiation is conveniently expressed in terms of the number of rads required to accomplish the kill of a fraction of the population. This is done rather than attempting to determine the amount of radiation to kill 100% of the population. Not only would it be difficult to do this experimentally but in addition the amount of radiation required is dependent upon the number of organisms in the population. Therefore, a method of procedure is used that kills 90% of the population present. The result is expressed as the D_{10} value, or the treatment required to reduce the population by a factor of 10.

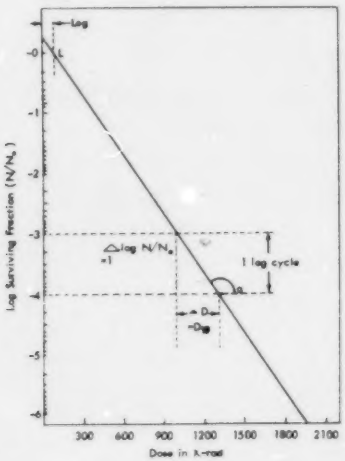

FIG. 17. Relationship between radiation dose and surviving fraction of microorganisms

In the case of treatment with ionizing radiation:

If N_0 = initial population
N = population after dose D
D = rads
D_{10} = rads to reduce population by a factor of 10 (10% survival)

then

$$\log_{10} \frac{N}{N_0} = - \frac{1}{D_{10}} D$$

D_{10} is commonly called the "decimal reduction dose", or the "D_{10}" value. D_{10} values for a number of organisms commonly associated with food are given in Table VIII, to give an indication of the differences due to species and spore formation.

Figure 17 shows a plot relating dose to surviving fraction of microorganisms. The $\log_{10}(N/N_0)$ plotted against the dose is a straight line

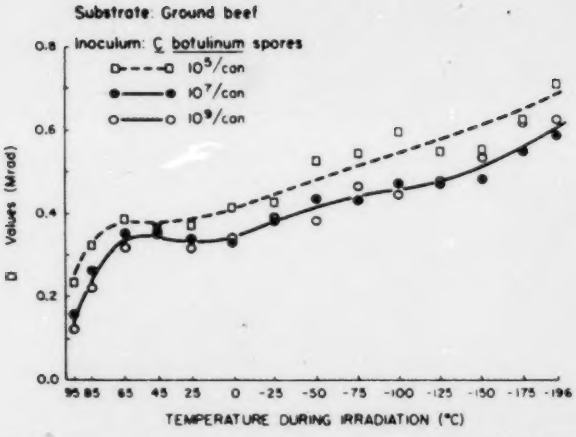

FIG. 18. Effect of temperature during irradiation on D_{10} values of spores of Clostridium botulinum

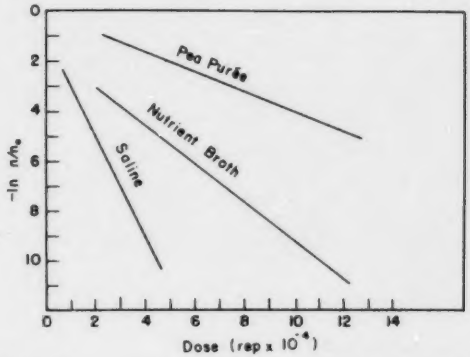

FIG. 19. Effects of gamma rays on Escherichia coli suspended in three different media

relationship, provided the radiation effect is the direct effect and one ionization causes a kill. Such an effect would be independent of dose rate, temperature, concentration of microorganisms, the physical state and composition of the medium. The efficiency of a given type of radiation would depend upon the target size and would relate to the number of ionizations produced per unit volume.

To a considerable degree the target theory explains the action of radiation on bacteria. Deviations from the straight line relationship mentioned above occur indicating that some additional mechanisms are involved. Figure 18 shows the effects of temperature (including physical state) and concentration of organisms upon the D_{10} value for Type C Clostridium botulinum spores. In this case the D_{10} value increases as the temperature is lowered. These data also demonstrate that the D_{10} value varies with concentration of spores. Figure 19 shows the effect of a

varying composition of medium on the surviving fraction of Escherichia coli.

Within wide limits dose-rate variation appears not to affect D_{10} values. Some types of ionizing radiation are more effective than others in killing bacteria. These effects appear to be related to the density of ionization produced, or perhaps more precisely, to the energy transferred to the absorber from the radiation. Gamma rays, X-rays and electron beams, however, appear to be about equivalent in their action upon bacteria.

It should be recognized that while departures from the simple relationship between dose and kill predicted by the target theory exist, the specific effect cannot be predicted. The effect of variables such as medium, composition, physical state, etc. on each organism must be determined.

More than one consideration applies to the irradiation of foods for the purpose of affecting bacteria present. One objective may be to reduce the number present in order to limit spoilage action, since bacterial spoilage normally is associated with growth of the contaminating bacteria. As the numbers increase, marked quality changes may occur in the food and one way to prevent these changes is to hold down the level of bacterial populations. This can be accomplished by irradiating the food sufficiently to reduce the population to a level such that the time to reach an undesired value is extended. In this way spoilage is delayed. Usually the food is subjected to otherwise normal handling. It is clear that this kind of use of radiation does not seek to destroy all bacteria present initially, but does permit some to survive. This kind of use of radiation has usually been referred to as pasteurization. This is not a strictly correct use of the term, but is one having wide acceptance.

Radiation pasteurization is not always a process of simple reduction of a bacterial population. As has been indicated, different organisms have different sensitivities to radiation and the kill of a population of mixed organisms is not uniform. The irradiation may lead to a changed flora and a different outgrowth pattern. Such changes may affect the ultimate spoilage of the food and need evaluation to protect consumers against unusual health hazards.

Radiation may also be used to control a specific organism, whose presence in a food may be objectionable for a reason such as constituting a health hazard. An example of this would be presence of Salmonellae. The radiation treatment may be designed to relate solely or primarily to such an organism, and the dose level to obtain an adequate reduction in numbers would be governed primarily by the D_{10} value of the organism. The term "radicidation" has been suggested for treatment by radiation to eliminate non-spore forming pathogens.

Finally, the objective of the irradiation may be to destroy all spoilage microorganisms present. This may be for the purpose of obtaining a sterile product, which, with suitable packing, will have an indefinite storage life at temperatures above those of refrigerator storage. In this case, consideration needs to be given to (a) elimination of all organisms whose growth would cause product spoilage, and/or (b) elimination of all organisms that might cause a consumer health hazard. The term "radappertization" has been suggested for this type of processing using ionizing radiation.

There is no absolute value for the amount of radiation to destroy all microorganisms present. The destruction of microorganisms follows a

statistical pattern and for sterile products, the objective is to reduce the probability of survival to less than one organism in an initial population of 10^{12} organisms. In attaining this objective, consideration is given to:

(a) the specific type of significant organisms,
(b) the initial inoculum level of these organisms,
(c) the D_{10} value of the organisms in relation to the D_{10} value of other organisms likely to be present.

For non-acid, low salt foods, the organisms of concern are the different types of Clostridium botulinum.

This spore-forming species can be present in foods and is hazardous to man because of toxin production. The D_{10} values for the various types of Cl. botulinum are somewhat different, but are all high (see Table VIII). This is the most radiation resistant group of organisms likely to be encountered in foods. The only organism more radiation resistant is Micrococcus radiodurans. Its occurrence is such that it has been largely ignored in determining the dose requirements for sterile products. Irradiation of foods to obtain sterility has been gauged in terms of D_{10} value for Cl. botulinum. All other organisms likely to be present are presumed to be destroyed by setting the process for the killing of Cl. botulinum.

The level of contamination of a food with the spores of Cl. botulinum is the remaining factor for dose determination. The viewpoint has been taken that the same standards which have been used in setting process schedules for heat sterilization of foods should be used for irradiation. The heat process schedules assume an initial population of 10^{11} spores per unit or package. Hence, to reach a population of less than one, the reduction accomplished by heat is 12 log cycles. To accomplish this with radiation requires 12 times the D_{10} value determined for Cl. botulinum, and this has led to the use of 4.5 Mrad as the sterilization dose.

This requirement applies to non-acid low-salt high-moisture foods. Foods having chemical compositions that are different may require less radiation, since Cl. botulinum may not grow and produce toxin in such foods. Arguments have been advanced against the use of this high dose requirement because of the unlikelihood of an initial population of 10^{11} spores ever being encountered. Arguments supporting the 4.5 Mrad dose are the long-term success record of the heat process for foods and the viewpoint that statistically it makes no difference whether 10^{11} organisms exist in one unit (e.g. a can of product) or are distributed in a large number of units.

5.2.3. Insects

Foods contaminated with insects are generally regarded as unfit for human consumption. In some cases the transportation of insect-infested foods from one area to another results in distributing the insect. If the insect is harmful, say to certain crops, such food movement may be prohibited, or the product may be subject to control and application of some processes, such as fumigation to destroy the infestation.

Radiation can be a useful agent for controlling insect infestation of foods. We shall consider only the application of radiation to foods and not the use of radiation for sterilization of insects per se, as a general population control measure. Insects are relatively insensitive to radiation.

As with other organisms, the effects of radiation on insects are closely related to the effects on constituent cells. For cells, the sensitivity to radiation is in direct proportion to their reproductive activity and inversely proportional to the degree of differentiation. During the larvae period of insects, very little cell division occurs. Cell division and differentiation of tissues occur during embryonic development in the egg and there are brief periods just before moulting (if this process is normal) and in later stages of pupation. Dividing insect cells are as sensitive to radiation as are cells of vertebrates, but the generally static life of adult insects makes them insensitive to radiation. Certain cells of the adult, however, maintain a metabolic activity, namely the cells of the gonads and these are sensitive to radiation. Hence relatively low doses cause sterilization or cause genetically deranged gametes. Higher doses are required for a lethal effect.

The general deteriorative effects of radiation on insects are: lethality, "knock down" (apparent lethality, followed by recovery), reduced longevity, delayed moulting, sterility, reduction of egg hatch, delay of development, reduction of food consumption and respiration inhibition. These effects occur at certain dose levels. Reverse effects at other (lower) dose levels have been observed, including increased longevity, increased egg laying, increase of egg hatch, and stimulation of respiration.

The minimum dose levels of gamma radiation to arrest development of certain insects and a mite are shown in Table IX. Similar data, to produce sterility in adults, are shown in Table X. These show that moths are more resistant to the effects of radiation than are the weevils. It must be pointed out that at life stages below the adult, radiation produces sterility in these insect stages. Thus, if a larva develops from an irradiated egg, it will not develop to the pupa stage. If an adult develops from an irradiated pupa, the adult will be sterile. These tables show that the following dose ranges apply: 13 to 25 krad permit some development of eggs and larvae, but prevent development to the adult stage. 40 to 100 krad prevent all eggs, larvae and pupae from developing to the next stage. Beetles in the adult stage require 13 to 25 krad to produce sterility, whereas moths require 45 to 100 krad. The mite tested, requires 25 to 45 krad.

Control of insect infestations in foods may be considered in these general terms: For immediate lethality, doses in the range of 300 to 500 krad would be required. A dose of 100 krad would probably be sufficient if lethality within a few days is the goal; a dose of 25 krad would be sufficient if the goal was lethality within a few weeks and sterility of the living insects. From a practical standpoint, the dose selection can be made on the basis of the tolerance that could be allowed.

Radiation given in a single dose is more effective than if given in increments. For certain insects, raising the temperature prior to irradiation sensitizes them to radiation. Reduction of the atmosphere oxygen pressure increases resistance.

5.2.4. Yeasts and moulds

Yeasts and moulds are frequently present on foods, and their outgrowth can produce changes which are undesirable and cause food spoilage. Yeasts and mould appear to be about as sensitive to radiation as non-spore forming bacteria. There is substantial variation in sensitivity according to species.

TABLE IX. MINIMUM DOSAGE OF GAMMA RADIATION COMPLETELY ARRESTING DEVELOPMENT OF STORED-PRODUCT INSECTS AND A MITE

Organism	Stage exposed	Stage observed for effect	Dosage (krad)				
			13.2	17.5	25	40	100
LEPIDOPTERA							
Plodia interpunctella	Egg	Larva				X---------X	
	Egg	Adult	X---------X				
	Larva	Pupa					>X
	Larva	Adult	X				
	Pupa	Adult					>X
Sitotroga cerealella	Egg	Larva					>X
	Egg	Adult	X---------X				
	Larva	Adult	X---------X				
	Pupa	Adult					>X
COLEOPTERA							
Tribolium confusum	Egg	Larva					>X
	Larva	Larva [a]	X				
	Larva	Pupa					>X
	Larva	Adult	X [b]				
	Pupa	Adult					>X
Lasioderma serricorne	Egg	Larva					>X
	Larva	Larva [a]				X---------X	
	Larva	Pupa					>X
	Larva	Adult	X [c]				
	Pupa	Adult					>X
Rhyzopertha dominica	Larva	Pupa					>X
	Larva	Adult		X-------X [d]			
	Pupa	Adult					>X
Attagenus piceus	Egg	Larva					>X
	Larva	Larva [a]			X--------X		
	Larva	Pupa	X				
	Larva	Adult	X				
	Pupa	Adult				X---------X	
Trogoderma glabrum	Egg	Larva				X---------X	
	Larva	Larva [a]		X-------X			
	Larva	Pupa	X				
	Larva	Adult	X				
	Pupa	Adult				X---------X	
ACARINA							
Acarus siro	Egg	Larva					>X
	Larva	Adult			X--------X		
	Hypopus	Adult				X---------X	

[a] Based on data obtained 21 days after exposure.
[b] One survivor after exposure of 45 krad.
[c] One survivor after exposure of 100 krad.
[d] One survivor after exposure of 45 krad.

TABLE X. MINIMUM DOSAGE OF GAMMA RADIATION PRODUCING STERILITY IN 100% EXPOSED ADULT STORED-PRODUCT INSECTS AND A MITE

Organism	Sex exposed	Dosage (krad)				
		13.2	17.5	25	45	100
LEPIDOPTERA						
Plodia interpunctella	Male					>X
	Female					>X
Sitotroga cerealella	Male					>X
	Female				X---------X	
COLEOPTERA						
Tribolium confusum	Male & female	X---------X				
Lasioderma serricorne	Male & female		X---------X			
Attagenus piceus	Male	X---------X				
	Female	X---------X				
Trogoderma glabrum	Male		X---------X			
	Female	X				
ACARINA						
Acarus siro	Male & female			X--------X		

Considerable work has been done on the control of moulds which cause rotting or softening of certain fruits. In some cases, the radiation dose to kill the moulds is higher than the fruit can tolerate, and the tissue becomes soft and susceptible to rotting due to the degradation of pectic substances. Rather remarkable results have been obtained with the strawberry in preventing the development of a mould that causes considerable economic loss during shipment and marketing of this fruit. Approximately 200 krad has been demonstrated to markedly extend the market life of strawberries during normal marketing. About the same radiation dose will control moulding in serveral other fruits, among them being citrus fruits and apples.

Yeasts do not cause a great deal of trouble with fresh fruits, but are the cause of spoilage in fruit juices and other types of fruit products. The radiation dose necessary to control yeast growth is often high enough to cause flavour changes. This can be corrected by the use of heat treatment, combined with a lower dose of radiation. However, in this case, the cost of the double process makes such a process uneconomical.

5.2.5. Animal parasites

This group of organisms include parasitic worms which can infest certain foods. Some of these can infest man and, because of this fact, are a matter of concern when present in foods. Irradiation of the infested food is a possible method of controlling these organisms.

TABLE XI. FOOD-BORNE HELMINTHS

Helminth	Carrier food	Human disease
Trichinella spiralis	Pork	Trichinosis
Taenia solium	Pork	Pork tape worm
Taenia saginata	Beef	Beef tapeworm
Clonorchis sinenis	Fish	Liver fluke
Diphyllobothrium latum	Fish	Fish tapeworm
Paragonimus westermani	Crayfish	Lung fluke
Ascaris lumbricoides	Raw vegetable	Intestinal worms
Fasciolapsis buski	Raw fruit-water plants	Intestinal fluke
Fasciola hepatica	Watercress, lettuce	Liver fluke
Anisakis marina	Herring	Intestinal worms

The principal helminths of interest in connection with foods are listed in Table XI.

These organisms exhibit several forms during their life cycle, but normally are in only one form as a food contaminant. Radiation is effective regardless of the form. For larval forms, with increasing dosage, the effects are: sterility of the adult females; inhibition of normal maturation and localization; death. The requirement for sterilization of Trichinella spiralis is about 12 krad, for inhibition of maturation about 20 to 30 krad and for death about 750 krad. For the devitalization of the tapeworm of beef 300 krad to 500 krad are necessary.

5.2.6. Plants

A great deal of information is available on the effects of radiation on living plants. Interest in this area in connection with the irradiation of foods is necessarily limited, and effects on growth and reproduction are outside of this interest. Interest exists, however, for those foods which exhibit certain life processes during the period between harvest and consumption. These foods are many raw fruits and vegetables.

5.2.6.1. Fruits

Fruits may be classified according to their respiratory behaviour during ripening as either of the climacteric or non-climacteric class. Climacteric fruits exhibit a slowly declining respiration rate which reaches a minimum just before the onset of ripening. As ripening begins, respiration increases greatly and reaches a peak as the fruit becomes ripe. Final degradation of the fruit (senescence) is accompanied by a declining rate of respiration. Non-climacteric fruits are often fully ripe at harvest and show a slowly declining rate of respiration without any period of peak activity.

For climacteric fruits the pre-climateric respiration minimum is a key point with regard to response to stimuli, including radiation. Irradi-

ation of fruits in the pre-climacteric stage produces a greater response to radiation than in fruits treated beyond the onset of the climacteric.

Figure 20 presents data showing the effect of gamma radiation on ethylene production in the pre-climacteric Bartlett pears. Pears irradiated at the climacteric peak show a decrease in ethylene production. For relatively high doses (300-400 krad) irradiation of pears in the pre-climacteric stage, ripening is inhibited and cannot subsequently be brought about by exposure to ethylene.

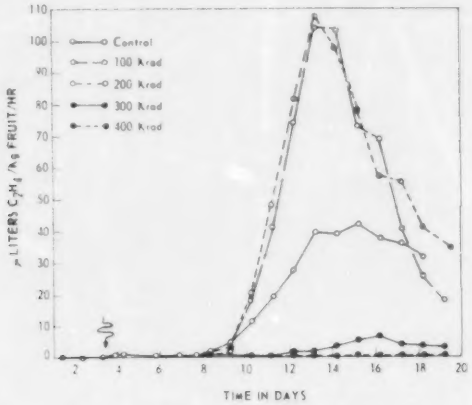

FIG. 20. Effect of gamma irradiation on ethylene production by Bartlett pears

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Not all fruit behaves as do pears. Peaches and nectarines, for example, when irradiated with doses as high as 600 krad are stimulated to ripen. Figure 21 shows data on the changes in respiration rate of late Elberta peaches caused by irradiation. Figure 22 shows the changes in rate of ethylene production for this fruit. Unlike pears, the peaches ripen with high doses and remain sensitive to ethylene.

Since the response of climacteric fruits to radiation is related to the position in the climacteric sequence, the use of radiation in irradiating fruits for preservation or other purposes must take this into account in order to minimize adverse effects, and to secure desirable ones.

Non-climacteric fruits show a response to radiation somewhat similar to climacteric. Respiration rate is increased, as is ethylene production. Since ripening is not involved, these effects do not indicate climacteric induction.

Radiation can produce changes in chemical composition of fruits. Such changes include: destruction of ascorbic acid, conversion of protopectin to pectin and pectate, degradation of cellulose and starch, destruction of certain acids such as malic (in apples) and pigment changes. Texture changes appear to be associated with pectin changes and can be a limiting factor in the amount of radiation which can be employed. Softening can be reversed by treating some fruit with calcium salts. Reversal of the softening of strawberries occurs spontaneously on storage after irradiation.

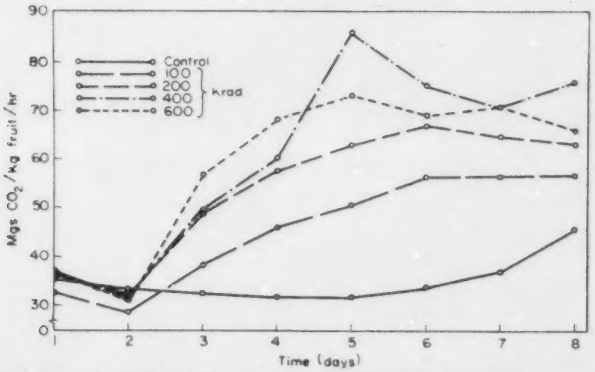

FIG. 21. Effect of gamma irradiation on the respiratory rate of Late Elberta peaches

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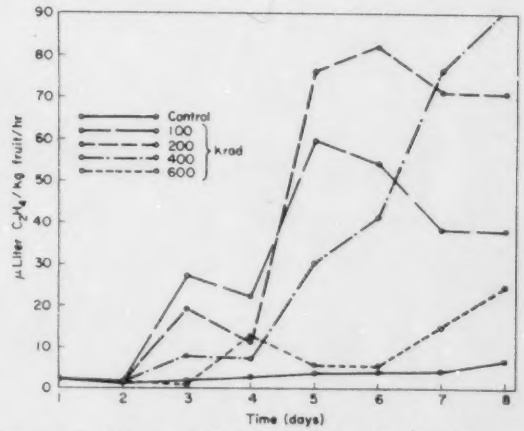

FIG. 22. Effect of gamma irradiation on rate of ethylene production by Late Elberta peaches

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5.2.6.2. Vegetables

Raw vegetables like raw fruits consist of slowly metabolizing tissue. Radiation can affect the rate of this metabolism, the specific effect being related to the radiation dose. Most studies have been with doses in the krad range. Observed effects of radiation have included: changes in rate of respiration, inhibition of normal growth and senescence and changes in chemical composition. Figure 23 indicates the effect of radiation on the respiration rate of potato tubers. A quick and large increase in rate of oxygen uptake occurs shortly after irradiation, followed by gradual reduction. Too low or too high a dose does not produce this effect.

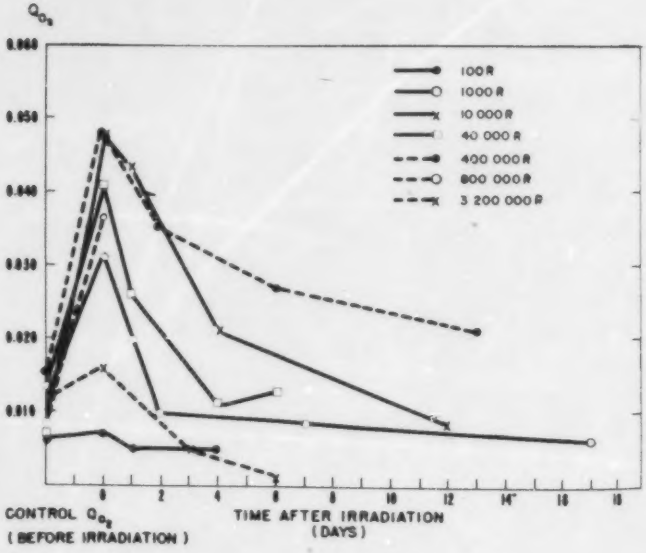

FIG.23. The effect of gamma radiation upon the oxygen uptake of potato tubers

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Root vegetables, such as potatoes and onions will not sprout after irradiation. Greening of the skin in the presence of light is inhibited. Potatoes, irradiated at too high a level will rot more rapidly. The irradiation of mushrooms causes the cao and veil not to open and this markedly prolongs the market life of the product. Irradiated asparagus spears do not lengthen. It has been postulated that these effects of interference with normal growth and senescence are related to an interference with cell division.

In potatoes, irradiation does not change the carbohydrate content. It does not reduce the concentration of growth promoting compounds, but does reduce the ascorbic acid content.

6. PRESERVATION OF FOODS

The principal reasons for preserving foods are to make them available at times after production and harvest or at locations different from production and harvest. As has been suggested in earlier sections of this manual, there are a number of methods by which foods spoil or become unsuitable for consumption. Likewise there are in use a variety of preservation methods to prevent spoilage. Assessment of spoilage and preservation requires definition of quality factors which describe suitable and unsuitable foods.

TABLE XII. COMPOSITION OF SELECTED FOODS -- EDIBLE PORTIONS

Food	Per cent fat	Per cent carbo-hydrates	Per cent protein
Apple, raw, pared	0.3	14.1	0.2
Banana, raw, common	0.2	22.2	1.1
Beans, raw, white	1.6	61.3	22.3
Beef, raw, round	12.3	0.0	20.2
Cabbage, raw, common	0.2	5.4	1.3
Cauliflower, raw	0.2	5.2	2.7
Cheese, cheddar	32.2	2.1	25.0
Chicken, raw, skinned			
Light meat	4.9	0.0	18.6
Cod, raw	0.3	0.0	17.6
Eggs, chicken, raw, whole	11.5	0.9	12.9
Haddock, raw	0.1	0.0	18.3
Lamb, leg, raw	21.0	0.0	16.9
Milk, cow, whole	3.7	4.9	3.5
Orange, raw, peeled	0.2	12.2	1.0
Pork, loin, raw	28.0	0.0	16.4
Potatoes, white, raw	0.1	17.1	2.1
Rice, white, polished, raw	0.4	80.4	6.7
Shrimp, raw	0.8	1.5	18.1
Soy beans, mature, raw	17.7	33.5	34.1
Sweet potato, raw	0.4	26.3	1.7
Tuna, blue fin, raw	4.1	0.0	25.2
Veal, loin, raw	15.0	0.0	18.6
Wheat flour, bread	1.1	74.7	11.8

6.1. Quality factors important to foods

6.1.1. Nutritive value

The principal function of foods is to nourish and sustain the life of the consumer. Hence foods must be the source of the nutrients required for these functions. A major consideration is that the foods provide the energy needed for life. The caloric content of a food is a major quality attribute. The macro-constituents of food (other than water) are fats, carbohydrates and protein. These all can be utilized by the consumer to supply energy.

TABLE XIII. ESTIMATE OF CALORIC REQUIREMENTS OF ADULTS ACCORDING TO AGE (calories per day; mean temperature 10°C)

Age	Men	Women
20 - 30	3200	2300
30 - 40	3104	2231
40 - 50	3008	2162
50 - 60	2768	1990
60 - 70	2528	1817
70	2208	1587

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The approximate caloric content per gram of these constituents as determined by heats of combustion of digested nutrients is as follows:

Fat	9 cal
Carbohydrate	4 cal
Protein	4 cal

The physiological energy obtained by the consumer differs somewhat from these values depending on the type of food and the individual food. Typical compositions of selected foods are shown in Table XII.

The physiological energy requirement of a human is a function of age, sex, size, environment and activity of the individual. Table XIII gives estimates of caloric requirements of adults according to age.

Fats, carbohydrates and proteins, while sources of energy, also have other actions in the functioning of the body. Fats in addition to providing energy are carriers of micro nutrients such as the fat-soluble vitamins. Proteins are sources of amino acids. Certain amino acids are regarded as "essential" in human nutrition in that they must be present in the consumed food as they cannot be synthesized by the human. Other amino acids which occur in many foods are not in this essential category but are utilized by the body. Proteins, and foods containing them, therefore can be rated according to their amino acid composition, both as to which amino acids are present and the amounts of each. The need for particular amino acids varies with age, children having special requirements. In general, proteins of animal origin are of higher nutritional quality in terms of an index of essential amino acid composition than are proteins of plant origin. Proteins of plant origin may be lacking in one or more essential amino acids. Proteins exist in every cell and are essential constituents of body tissues.

Vitamins and minerals are micro-constituents of foods that play key and complex roles in the body functions. Vitamins may be classified as fat soluble or as water soluble. Generally vitamins used in the body functions are obtained from the ingested foods. Minerals have no other sources than food and water taken into the body. Hence, the vitamin and

mineral contents of foods represent important quality indexes. Preservation methods or improper storage can reduce the vitamin content of a food, and in this way degrade its nutritional value.

It is recognized that good nutrition requires a proper balance of nutrients and while much in the area of nutrition has been learned, there is still insufficient knowledge to specify with precision the optimum levels for many nutrients. The determination of such levels is complicated by variations in needs with age, sex, size, environment and activity of individuals. For many reasons good nutrition is usually considered to result from a diet of a variety of foods, provided such a diet includes essential nutrients in appropriate amounts.

6.1.2. Safety

A food, even if nutritious, must not contain anything harmful to the consumer. Food hazards can be classified as chemical or biological in nature. Many chemical compounds are injurious to the healthy functioning of the body. Some are direct poisons capable of causing death or impaired health, while others affect body processes such as reproduction or lactation. If radioactive elements are contained in molecules making up a food, they will give off radiation which can cause changes in the tissues of the consumer which may interfere with their normal function. Abnormal "growths" or tumours can be produced in the body both by such radiation and toxic chemical agents. Such toxic agents may not always seriously harm the immediate consumers of the food, but may harm their progeny. These different effects have been variously named, such as toxic, cytotoxic, mutagenic, carcinogenic, etc.

Toxic chemical agents of the type just referred to may harm the body in several ways. Certain ones may naturally be present in the food, while others may be added either intentionally (e.g. preservatives) or accidentally. Certain microorganisms, especially bacteria and moulds, which contaminate foods may produce substances toxic to man.

Biological hazards generally result from the contamination of the food with an organism which can infect man and produce a disease condition. These organisms include viruses, bacteria and helminths.

There should be a system of quality assessment set up for detecting food contaminants having the capability of harming the consumer, in order to prevent them from entering the food chain. Also, decontamination processes must be devised and used. The nutritive value and safety of food should be viewed as being of prime importance.

6.1.3. Sensory acceptability

Sensory characteristics include those quality aspects of a food which one way or another are discernible by the senses of the consumer. These characteristics usually are used in his acceptance and selection of food and govern, to a considerable degree, the pleasure and satisfaction he derives from its consumption. Sensory characteristics include: colour, odour, taste, texture, shape, size, tenderness, viscosity, uniformity, non-uniformity, temperature, etc. These are subjective characteristics and their meaning to an individual is based on many human factors such as conditioning, experience, custom, social status, as well as apparently

TABLE XIV. SCALE OF IRRADIATION FLAVOUR INTENSITY

No.	Degree of flavour intensity
1	Imperceptible
2	Slightly perceptible
3	Perceptible
4	Slightly pronounced
5	Moderately pronounced
6	Pronounced
7	Very pronounced

inherent preferences. They are important characteristics because under many circumstances they govern what is purchased and eaten. Regardless of nutritional value, variations in these sensory characteristics frequently affect the market value of a food, since consumer demand will vary according to preference.

Efforts have been made to devise instrumental or chemical methods of measuring these sensory characteristics. Such approaches have met with varying success; some are used regularly in research and product evaluation or in process control. In many cases, however, the subjective reaction of the human senses to a food characteristic is too complex to be obtained in such an objective way, and the only really dependable methods employ human observers who use their sensory capabilities in a reasonably precise fashion to evaluate a food. This type of evaluation has been highly developed. It usually involves "panel" testing; in which a group of individuals examine the food and each makes a judgment as to a particular quality characteristic. The individual judgments are then brought together and the group judgment ascertained. Under some circumstances the judgment of a single tester may be the only one obtained.

Panels of judges are of two general types: (1) expert or difference panels, and (2) consumer acceptance panels. The former, using qualified knowledgeable experts are called upon to distinguish differences between two or more samples of a food. Consumer panels, on the other hand, can offer an indication of the acceptance of the food by the ultimate user.

Various techniques have been devised for carrying out panel evaluations. A common technique for difference testing is to use the triangle test, in which the judge is given three samples, two of which are identical and is asked to determine which two of the three are the same. A sufficient number of observations to provide for statistical treatment with significant results will establish the existence or absence of a difference.

Expert panels can be used to quantify a difference in a particular sensory characteristic by employment of a scale appropriate to the characteristic. Such a scale is shown in Table XIV.

Expert panels usually are familiar with the food and the characteristic under consideration. It is usually desirable to provide for training and selection of panel members. Only those having demonstrated consistent sensitivity to the characteristic under consideration should be used. It is

frequently desirable to calibrate an expert panel by obtaining group agreement on the rating of one or more standard samples.

Consumer panels basically respond to the question of whether they like or dislike a food. A "hedonic" scale of one to nine is frequently employed in this determination. Such a scale is shown in Table XV. More than one sample may be rated at the same "sitting". An example of a consumer rating sheet with the common hedonic scale of nine is shown in Table XVI.

Note that the judges in both expert and consumer panels are given word descriptions to aid them in their judgments. Problems arise in the interpretation of these word descriptions by individual testers. None the less, careful applications of these techniques can lead to reliable results. Care should be exercised to avoid communication among judges during the evaluation. Expert panels generally use only a relatively small number of judges, whereas consumer panels usually are much larger, their reliability being somewhat dependent upon size. Consumer panel members must represent the ultimate consumer and thus they are not specially trained or conditioned for making such evaluation, but rely on their own likes or dislikes of the food.

An important aspect of certain foods relates to their ability to perform a particular function in the preparation of a compounded food. Flour, for example, must be capable of producing a loaf of bread with suitable texture, and while this functional property is not apparent until the food is put to its intended use, it is inherent in its value. The degree to which such a food performs in a functional way is, therefore, an important quality characteristic that must be measured.

6.1.4. Stability

The period of time that a food will keep in condition that is satisfactory is important. This period can be of indefinite length or it can be of limited duration, depending on the use of the food. The choice of limited or indefinite preservation relates to the need or objective of storage and to what is attainable. Very often, the storage time requirement is only a

TABLE XV. HEDONIC SCALE

Numerical designation	Word description
1	Like extremely
2	Like very much
3	Like moderately
4	Like slightly
5	Neither like nor dislike
6	Dislike slightly
7	Dislike moderately
8	Dislike very much
9	Dislike extremely

TABLE XVI. PREFERENCE TEST RATING SHEET

Sample No.					
	Like extremely	Like extremely	Like extremely	Like extremely	Like extremely
	Like very much	Like very much	Like very much	Like very much	Like very much
	Like moderately	Like moderately	Like moderately	Like moderately	Like moderately
	Like slightly	Like slightly	Like slightly	Like slightly	Like slightly
	Neither like nor dislike	Neither like nor dislike	Neither like nor dislike	Neither like nor dislike	Neither like nor dislike
	Dislike slightly	Dislike slightly	Dislike slightly	Dislike slightly	Dislike slightly
	Dislike moderately	Dislike moderately	Dislike moderately	Dislike moderately	Dislike moderately
	Dislike very much	Dislike very much	Dislike very much	Dislike very much	Dislike very much
	Dislike extremely	Dislike extremely	Dislike extremely	Dislike extremely	Dislike extremely

Please check for each sample the one set of words which best describe your reaction to it.

matter of days and production, harvesting and processing can be geared to the circumstance. On the other hand, certain foods, such as those produced seasonally, need to be stored from one harvest to the next or transported long distances. In such cases, the preservation period may be many months or even longer.

The maintaining of stability of the food during the preservation period is essential. Many of the quality indexes referred to above, provide the means of judging the amount of change during storage, and serve as guides in determining the allowable amount of change that must be tolerated.

6.2. Spoilage agents for foods

Degradation of foods occurs in several ways, which may be classified as biological, chemical and physical. The particular spoilage pattern of a given food tends to be characteristic of that food under comparable preservation conditions. The condition of the product, type and extent of contamination, and the temperature of storage, are factors that markedly affect the rate of deterioration in quality.

6.2.1. Biological spoilage

A common kind of spoilage of a biological nature is associated with the contamination of the food with organisms whose growth produces changes in the food regarded as undesirable. Bacteria, yeasts and moulds are the

principal organisms which account for this type of spoilage. The food provides the nutrients for the growth of these microorganisms. Generally appropriate conditions of temperature and moisture are required in order to permit their growth. Foods tend to be contaminated with a characteristic flora and the initial microbial population level is an important aspect of the spoilage pattern.

In a somewhat different manner, the contamination of a food with insects can "spoil" the food. The spoilage in this case may be the objectionable presence of the insects themselves, or it may be actual damage to the food.

Contamination of a food with pathogenic microorganisms may not produce spoilage of a sensory nature, but if such contamination constitutes a health hazard, this can be considered as a form of spoilage.

Some foods, such as fruits and vegetables, are themselves living organisms and, as they are stored, the normal life processes continue, leading to senescence, characteristic softening and deterioration. Ultimately, this development leads to changes which make the foods unacceptable.

6.2.2. Chemical spoilage

Chemical spoilage usually results from reaction of food components with one another, or from reaction of the food with its environment. The reaction of sugars with proteins (Maillard or browning reaction) is an example of the former, in which this sugar-protein reaction produces undesirable flavour and colour changes. Rancidity development in a fat is an example of a food deteriorating through reaction with its environment (atmosphere oxygen). Chemical spoilage can be occasioned by active native enzymes present in the food.

6.2.3. Physical spoilage

Physical spoilage is perhaps the least important kind of spoilage. It usually results from bruising, cutting or breaking a food during harvesting, transporting or handling. It can also result from loss of moisture which changes the texture of the product or from the uptake of moisture from the surroundings to a point where mould growth can take place and spoil the product.

6.3. Common food preservation methods

Most food preservation methods used today had their origin in prehistoric times. They have been refined and improved, elaborated, placed on a scientific basis, controlled and extended in application. The following is a list of these ancient methods:

(a) Drying, including dehydration
(b) Refrigeration (including freezing)
(c) Chemical preservation (e.g. salting)
(d) Fermentation
(e) Heat treatment (cooking, roasting)
(f) Packaging

To these prehistoric methods have been added three new processes:

(a) Canning
(b) Controlled atmosphere
(c) Irradiation

Canning was invented in the beginning of the nineteenth century. Controlled atmosphere handling of foods, especially fruits and vegetables, is a very recent development. Irradiation is a basically new approach to food preservation.

The established preservation methods in all their multitudinous applications involve many steps, unit operations and the use of specially designed and built equipment. They accomplish the purposes for which they are carried out, but cannot be regarded as without problems or without opportunities for improvement. Research to improve food preservation methods is an important activity in food science and technology today.

7. RADIATION PRESERVATION OF FOODS

7.1. General effects of radiation on foods

The effects of radiation useful in preserving foods generally relate to the effects of radiation on living organisms. With few exceptions the effects of radiation causing changes on the intrinsic characteristics of foods are not of interest and actually may present problems. The general kinds of preservative actions are as follows:

(a) Control of microbial spoilage
  (i) Sterilization
  (ii) Pasteurization
(b) Control of microorganisms which are a health problem
(c) Control of helminths
(d) Control of insects
  (i) To prevent food damage
  (ii) To prevent product contamination for aesthetic reasons or for control of the distribution of insects
(e) Delay of senescence (of living foods)

In addition to these preservative effects, radiation can tenderize some foods, which in certain cases can be regarded as a product improvement.

The different kinds of applications require different amounts of radiation. For convenience, they can be classified as (1) high dose (1-5 Mrad), and (2) low dose (< 1 Mrad). In general high dose treatments yield products that are sterile, or essentially so, and which, when suitably packaged, will keep indefinitely. The high dose is required not only to kill vegetative bacteria, moulds and yeast, but also spores. Viruses are generally not considered presently in such applications due to the high doses required. Enzymes, if present, likewise are not inactivated by the radiation, but must be controlled by other means.

Low dose treatments are concerned with reduction of a microbial population, the control of organisms larger than bacteria, and the control of senescence of live foods.

7.2. High dose irradiation of foods

7.2.1. Meats and poultry

The objective of the treatment is to produce a product that will keep without refrigeration. The requirements to do this are:

(a) A radiation dose sufficient to destroy the most resistant strain of Cl. botulinum. For low salt non-acid meats this requires about 4.5 Mrad.

(b) The packaging of the product in a tight container to prevent microbial contamination after irradiation. A conventional metal container can accomplish this.

(c) Inactivation of the enzymes native to the products; heating to approximately 70°C accomplishes this.

The relatively high dose requirement occasions a major problem with these products. Under certain conditions a typical foreign flavour develops which affects consumer acceptance. This flavour is similar to but not identical with that associated with heat scorching and has been the subject of a great deal of study. Its intensity is dose dependent and meats from different kinds of animals exhibit it at different intensities for the same dose. Of the common commercial meats, beef develops the greatest flavour intensity. Pork and chicken are substantially less sensitive, and lamb and veal take an intermediate position.

Efforts have been made to identify the compounds responsible for this off flavour. It has been reported that methional, 1-nonanal and phenyl-acetaldehyde are present in the ratio 20 to 2 to 1, respectively, and are the three substances formed on irradiation of beef which are the most important contributors to the characteristic irradiation odour. These three compounds are not, however, the only ones formed when meats are irradiated.

Direct bond cleavage of the various compounds making up meat accounts for many compounds that have been isolated. Lipids give rise to n-alkanes, n-alkenes, and n-alkynes. Sterols yield normal and isoalkanes. Proteins and peptides do not cleave at the peptide bond but at the side chains, giving rise again to hydrocarbons such as n-alkanes, benzene and toluene. Sulphur containing proteins yields sulphides, disulphides and mercaptans.

Despite the knowledge of the compounds responsible for the undesirable flavour of irradiated meats, methods to prevent or suppress it have not been readily forthcoming. The best method devised so far has been irradiation at sub-freezing temperatures (-30 to -80°C). This suggests that the flavour compounds are formed not by direct action of the radiation but by indirect action of free radicals, probably originating in the water present. Lowering the temperature apparently eliminates the liquid phase immobilizing the free radicals and preventing their interaction with meat flavour constituents.

Figure 24 shows the variations of irradiation flavour intensity of beef with irradiation temperature at 3 and 6 Mrad. The amount of irradiation flavour which may be tolerated has been studied with the objective of avoiding the use of very low temperatures. Table XVII shows the results of one study on ham. On the nine-point hedonic scale a rating of 6 is considered

satisfactory. In the case of ham, at the dose level used, irradiation at -40°C is adequate to control the flavour change.

Since part of the bactericidal action of radiation is due to the indirect effect, it is reasonable to anticipate that irradiation at sub-freezing temperatures would affect this also. For the effect of temperature during irradiation on spores of Cl. botulinum see Fig. 18. Fortunately it appears only a small increase in dose to kill Cl. botulinum is needed relative to the large effect on flavour, making the overall value of low temperature irradiation a gain. This does point to the need for careful determination of sterilizing dose for the product in question under the particular conditions

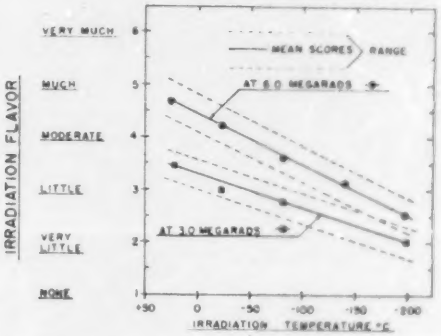

FIG. 24. Expert panel irradiation intensity scores of beefsteaks as a function of temperature and dose

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TABLE XVII. EFFECT OF IRRADIATION TEMPERATURE ON PREFERENCE RATINGS* OF IRRADIATED HAM

Storage (months)	n[a]	3.5 - 4.4 Mrad at °C				Unirradiated control
		+5	-18	-40	-80	
1	30	-	5.9	5.9	6.8	7.5
1	30	5.6	6.1	6.4	7.1	6.9
4	30	5.5	5.8	5.6	6.6	6.1
12	32	5.4	-	-	6.2	6.9
12	32	6.1	-	-	6.8	6.4
Overall average		5.65	5.93	5.97	6.70	6.76

* Nine-point hedonic scale - 9 is "like extremely"; 1 is "dislike extremely"; 5 is "neither like nor dislike". Samples scoring above 5.0 are considered acceptable.

[a] n = Number of taste test panellists.

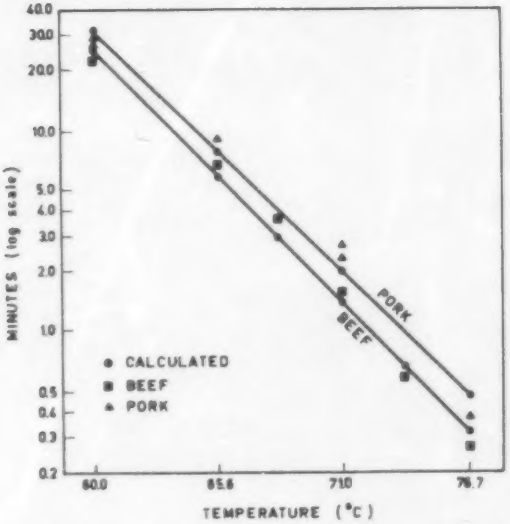

FIG. 25. Time versus temperature plot of regression lines for enzyme inactivation in irradiated beef and pork

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of irradiation treatment. Such a determination generally requires the "inoculated packs" approach; that is, the preparation of a number of units of the product inoculated with suitable numbers of the critical organism and then irradiated with various doses. After proper storage, the pack is examined for surviving organisms and the relationship of the kill obtained with dose absorbed is determined.

Meats containing added salt, such as ham, require a lower sterilization dose due to the inhibiting effect of salt on the growth and toxin formation of Cl. botulinum.

Since meats contain native enzymes, and since the radiation dose to produce sterility is substantially less than that needed for enzyme inactivation, the enzymes, unless otherwise inactivated, will cause changes in the meat. For example, tyrosine crystals have been observed to form as well as the development of bitter flavours brought about by enzyme action. The only effective means of enzyme inactivation presently available is heat. Figure 25 gives the time-temperature relationships to secure enzyme inactivation in beef and pork.

7.2.2. Marine and fresh water products

Many of the considerations relating to the high-dose irradiation of meats apply to marine and fresh water products. In general, however, these are not as subject to flavour change as are meats. Consequently, irradiated products such as shrimp, cod fish (cakes) and lobster having good sensory characteristics have been prepared.

7.2.3. Other foods

Bread has been reported acceptable when irradiated for the control of moulds with doses as high as 2 Mrad.

Milk and dairy products undergo severe flavour changes which make them unacceptable. Low doses on the surface of cheese have been successfully used to control surface mould growth.

Vegetables show varying responses to high dose radiation treatments. Texture and colour losses and large vitamin C destruction occur with many vegetables. Promising results have been reported for green beans, broccoli, brussel sprouts, sweet potatoes, and pumpkin. In general radiation sterilized vegetables do not appear to be superior to those produced by thermal processing. A combination of radiation and heat (850 krad plus five minutes at 100°C), however, has produced a sterile product of quality superior to thermally processed peas. The thermally processed peas were soft and yellow, whereas the irradiated peas were of good texture and green.

As with vegetables, most fruits are damaged with high doses of radiation and are generally unacceptable. Stable apple juice of good quality, on the other hand, can be prepared by a combination of heat and radiation.

Dry spices and related products such as vegetable flakes often contain large numbers of microorganisms which can contaminate the foods to which these products are applied. Irradiation at above 1 Mrad is effective in sterilizing these materials. In some cases there is a loss of flavour.

7.3. Low dose irradiation of foods

Low dose treatments generally provide product life extension or destroy a contaminating organism. Very often, irradiation is combined with another preservation method such as refrigeration. Because of the low dose, changes in the sensory characteristics are either too small to be detected or are of minor significance. Flavour changes in particular generally do not cause serious difficulties.

7.3.1. Meats and poultry

Raw meats and poultry are articles of food of great nutritional value in the human diet and are of economic importance. Due to the methods used in handling and preparation, meats and poultry become contaminated with bacteria that in time increase in numbers and spoil the products. In most marketing procedures, such products are kept under refrigeration, in order to extend the market life. If the meat or poultry items are treated by ionizing radiation, the bacterial populations will be markedly reduced and thus retard the growth of populations to numbers that will not be able to spoil the products.

However, under the best of handling and refrigeration, cold tolerant organisms will continue to grow and increase in number sufficient to eventually spoil the products. It is not economically practicable to use sufficient radiation to kill all the bacteria and prevent spoilage.

The principal spoilage microorganisms of fresh meats and poultry are of the genus Pseudomonas. This group of organisms is relatively sensitive to radiation, having a D_{10} value in the range of 2 to 5 krad. Hence, relatively small doses of radiation of 50 to 100 krad can effectively reduce the

population of this meat contaminant to a very low level. The subsequent outgrowth on storage is different from the normal. In the presence of oxygen the outgrowth is principally gram negative psychrophilic aerobes, such as Achromobacter and also sometimes certain yeasts. In the absence of oxygen, the outgrowth is primarily due to Lactobacteriaceae.

The use of antibiotics in combination with radiation has been investigated. The Microbacterium species are quite sensitive to certain antibiotics such as the tetracyclines, but are relatively resistant to radiation. The antibiotic action supplements that of the radiation and there is a further extending of the life of the product.

The lowest dose causing a detectable flavour change in fresh chicken has been reported to be about 100 krad. A somewhat similar threshold dose for beef probably applies. For pork it is substantially larger. The significance of these threshold doses in consumer acceptance of radiation pasteurized meats has not been fully determined. It is clear, however, that there is a fairly low dose-limitation for these particular meats, unless the irradiation is carried out at sub-freezing temperatures. Since a dose of the order of about 500 krad might be needed for Salmonella control, this might cause changes in flavour too great to be tolerated.

Raw meat tissues contain enzymes that bring about changes in the texture, flavour, odour and colour of the meat and even though a radiation dose is given sufficient to sterilize the meat, it will continue to deteriorate due to the action of the natural enzymes. The reason why the radiation does not prevent this type of spoilage is that the enzymes of the meat are very resistant to the action of the radiation and will continue to bring about deterioration, even though the meat has been irradiated at a high dose. As a rule, doses of radiation, sufficient to bring about an appreciable destruction of meat enzymes, bring about objectionable changes in the meat that make it unacceptable as food.

Pork can be contaminated with the parasite Trichinella spiralis. The reported dose to prevent maturation of the larvae in the host is between 20 and 50 krad. Such a dose would not cause detectable sensory changes in pork.

While irradiation is effective in retarding microbial spoilage of fresh meats at refrigeration temperatures, it does not control colour degradation and the formation of a liquid exudate known as drip or weep. Under some circumstances these two degradation processes are of a significance equal to that of microbial spoilage. This is especially true when meats are prepared as retail cuts. Hence in such a case, more than irradiation is needed to accomplish the preservation of fresh meats.

7.3.2. Marine and fresh water products

The principal reason for irradiating these raw products is to secure life extension through delay of microbial spoilage. It is expected that radiation will be used in conjunction with other preservation agents such as refrigeration. The value of such life extension lies in the opportunity it provides for economically transporting these products in the fresh condition greater distances than is now possible.

Marine and fresh water products are of several kinds and may be classified in more than one way; viz. fin fish, molluscs and crustacea; oily and non-oily. As might be expected, the response to radiation will vary with

the type. Table XVIII lists the maximum dose without detectable sensory change for a number of marine and fresh water products.

The spoilage organisms are different for the various products. Pseudomonas are the principal contaminants of white-fleshed fish and shrimp. Lactobacteriaceae cause oyster spoilage, and Pseudomonas, Achromobacter, Lactobacillus or Corynebacterium are the main spoilage flora of clams.

Figure 26 shows data in the survival of various organisms on Dover sole after irradiation on several levels. Yeasts, micrococci, and Achromobacter, although relatively few were present initially, survive even 400 krad in significant numbers. As a consequence of changes in flora, the outgrowth on storage is different from that without irradiation. The method of holding the food also enters into the outgrowth pattern. Under aerobic conditions Achromobacter can grow and, when present, can be the principal outgrowth organism. Achromobacter spoilage is typical of irradiated fin-fish fillets. When the irradiated product is stored under anaerobic conditions, the principal spoilage organisms are the Lactobacteriaceae. With the changes in flora, the spoilage characteristics are not always typical. Lactobacteriaceae, for example, cause a sour condition quite different from the typical odour of Pseudomonas spoilage.

TABLE XVIII. MAXIMUM RADIATION DOSE WITHOUT DETECTABLE SENSORY CHANGE AND LIFE EXTENSION UNDER GOOD REFRIGERATION (Marine and fresh water products)

Product	Dose (krad)	Life extension (days)
Fish - sea		
Haddock	200 - 250	18
Perch	350	18
Atlantic mackerel	350	30
Cod	150	18
Petrale sole	400	25-38
Grey sole	100	20
Halibut	400	12-23
Pollock	150	18
Fish - fresh water		
Channel cat	100	
Yellow perch	200	13-18
White fish	300	16-20
Molluscs		
Clams	800	
Oysters	200	
Crustacea		
Shrimp	200	5-14
King crab	200	14-37
Blue crab	250	28
Lobster	250	10-18

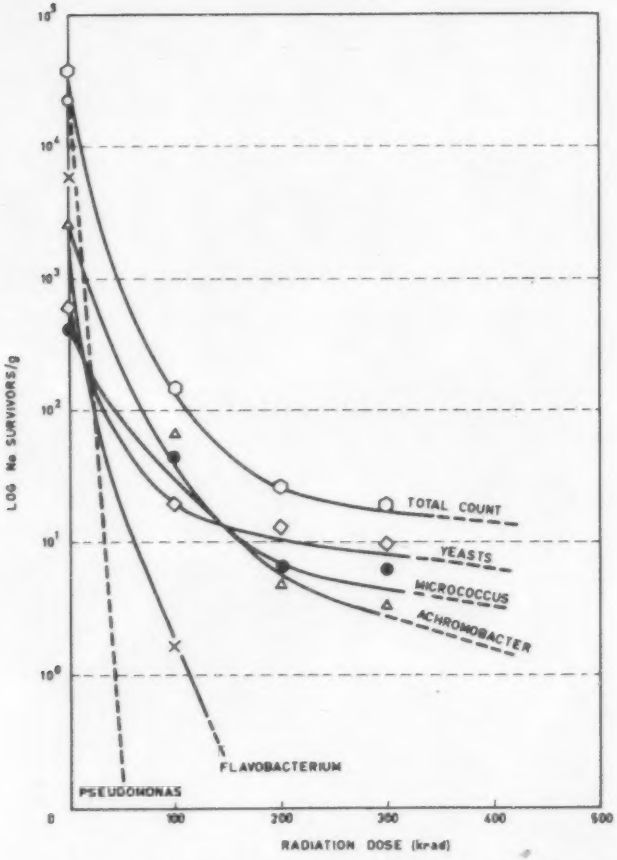

FIG. 26. Microbial flora change in Dover Sole as a result of irradiation

It appears that the best results are obtained with the irradiation of fresh fish. This is not only due to the better microbial condition of the fish when fresh but also is related to hypoxanthine formation in the muscle. This compound is formed in fish muscle upon storage, and is the product resulting from the disappearance of inosine monophosphate. The presence of the latter compound is associated with good flavoured fish and is independent of the microbial condition of the product. Stored fish, deficient in inosine monophosphate, is of inferior quality, regardless of microbial condition and is therefore less desirable than fresh fish for purposes of radiation preservation. This problem is accentuated by the very purpose of the irradiation, namely to obtain a life extension, and the inosine monophosphate deficiency may affect quality even before the onset of microbial spoilage.

Type E Cl. botulinum is associated with marine and fresh water foods under certain conditions. It is of special concern because of its ability to grow and produce toxin at temperatures as low as 3.5°C. The holding of

marine and fresh water foods for extended periods could represent a hazard from this organism if the temperature were not below 3.5°C. Since commercial handling can not always guarantee refrigeration as good as this, the actual hazard from higher temperatures has been evaluated through appropriate studies of inoculated product. These studies suggest there is variation in toxin formation among the sea and fresh water foods and each item requires individual study. Holding the temperature below 3.5°C is a uniformly safe practice. Some degree of protection is afforded by the cooking process which ordinarily is sufficient to inactivate any botulinum toxin which may have formed.

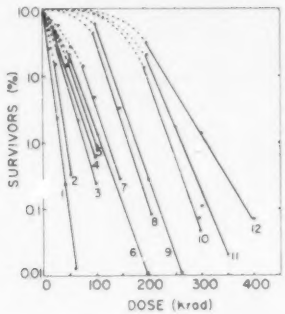

FIG. 27. Approximate dose response curves for spores of postharvest disease fungi, (1) Trichoderma viride, (2) Phomopsis citri, (3) Penicillium italicum, (4) Penicillium expansum, (5) Penicillium digitatum, (6) Geotrichum candidum, (7) Monilinia fructicola, (8) Botrytis cinerea, (9) Diplodia natalensis, (10) Rhizopus stolonifer, (11) Alternaria citri, (12) Cladosporium herbarum.

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7.3.3. Fruits

The reason for irradiating fruits may be one or more of the following:

(a) To delay microbial spoilage
(b) To control an insect infestation
(c) To delay senescence

Microbial spoilage of fruits is largely concerned with fungi. The degree of fungicidal effect desired considerably controls the radiation dose employed. With fruits having a short physiological life, such as strawberries, a temporary halt in lesion growth may be sufficient and as a consequence, the dose may be relatively small. With longer-lived fruits such as citrus, there is a need for a more complete inactivation of fungal lesions.

The approximate doses for inactivation for spores of the principal post harvest disease fungi associated with fruits are shown in Fig. 27.

The irradiation of fruits for post harvest disease control is complicated by the possibility of damage to certain characteristics of the fruit such as texture. Each kind of fruit, as well as individual varieties of fruits respond differently. In general useful effects seem possible in the range 50 to 300 krad.

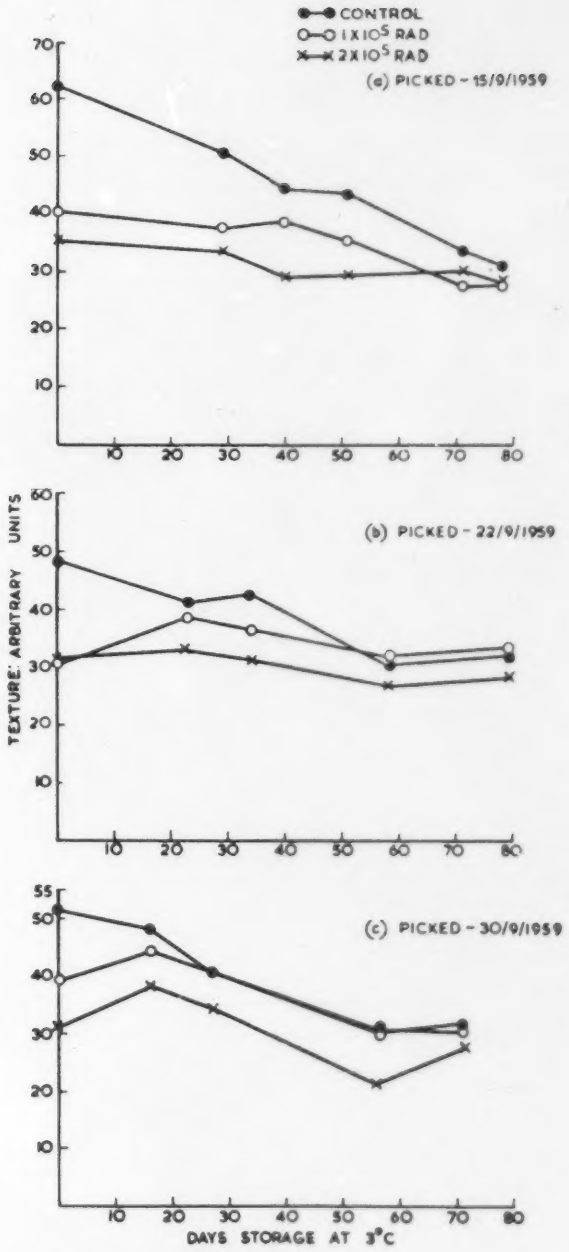

FIG. 28. The effects of gamma radiation on the texture of apples

The principal spoilage organism of strawberries is the grey mould Botrytis cinerea. This organism grows at low temperatures and consequently spoilage of strawberries cannot be controlled by refrigeration. Irradiation with 200 krad effectively delays spoilage. Storage must, however, be under refrigeration, since other organisms, such as Rhizopus stolonifer are relatively radiation resistant and will grow at higher temperatures.

Some fruits are subject to disease spoilage on storage. Among the fungi responsible, Penicillium expansum and Gloeosporium species in apples, and Botrytis cinerea in pears are frequently the cause of spoilage. 200 krad can effect a significant reduction of mould damage in apples. Texture changes in irradiated apples on storage are indicated in Fig. 28. It is believed that the observed immediate softening is associated with reduction in molecular weight of pectic substances. Other changes also occur, such as alteration of the organic acid content.

Citrus fruits are subject to a variety of fungi including Penicillium italicum (blue mould), Penicillium digitatum (green mould), Phytophthora spp. (brown rot) and a number of organisms associated with stem end rot such as Alternaria citri, Diaporthe citri, Pleospora herbarum, Botryosphaeria ribis and Diplodia natalensis. Up to 280 krad of gamma radiation do not cause damage to the internal quality of Shamouti oranges, but do cause pitting of the flavedo or outer layer of the peel. Similar damage has been reported for grapefruit. Peel damage can be avoided by reduction of the dose to 100 krad for oranges and 150 krad for grapefruit when the radiation is combined with heating for about five minutes at 53°C. These doses are effective against the Penicillium blue and green moulds. Alternaria rot, however, may be increased due to radiation-induced death of calyx tissue.

200 krad control Moniliria fructicola on peaches but causes unacceptable softening of the fruit. This dose can be reduced to 100 krad by combining the radiation with heating at 50°C for four minutes.

The combination of heat and radiation appears to be useful also for nectarines, cherries, and strawberries.

The softening caused by radiation can be largely offset by dipping the fruit in a $CaCl_2$ solution. Presumably this restores a calcium-pectin association which is disturbed by the radiation.

Irradiation of ripe tomatoes extends the normal storage period at 22-25°C to as much as 6 days or longer depending upon the level of the initial microbiological infection. Unripe fruit are unsuitable for irradiation (see below).

Insect infestation is of interest in connection with tropical fruits either fresh or dried. This interest stems from current prohibition of shipment of these fruits into potential market areas as a means of controlling the distribution of the contaminating insects. The fruits for which this kind of interest has been indicated are citrus (fruit fly), mango (seed weevil) Sternochetus mangiferae, and papaya (fruit fly). Fruit fly infestation can be controlled with 20 to 33 krad, Sternochetus mangiferae can be sterilized with 33 krad and killed with 75 krad.

Delay of senescence of fruits may be one of the more important applications of radiation. Of particular interest has been the delay of ripening of bananas. This fruit is frequently shipped to far distant markets and can be shipped successfully only in the green state. Irradiation in the green state delays the onset of natural ripening. The response of different varieties varies. The Montecristo variety treated with 40 krad will keep in the green

state five to six days longer at 26°C. Similar results have been reported with the Gros Michel and Valery varieties. The plantain, or cooking banana, on the other hand undergoes a greater delay in ripening, as much as nine days. Irradiation of mechanically injured green bananas or of ripe bananas is ineffective in extending their life. Bananas irradiated in the green state ripen normally with ethylene. A second inhibition of senescence at the ripe stage has been reported for bananas irradiated when green.

200 krad delays the ripening of papayas. A 10% loss of ascorbic acid in papayas occurs with irradiation with 100 to 150 krad.

Irradiation of unripe peaches with 300 krad accelerates carotenoid formation and intensifies anthocyanin formation and as a consequence intensifies the colour of the fruit. There is also a slower conversion of pectic substances.

The effect of radiation upon the ripening of tomatoes depends on the degree of ripeness of the fruit at the time of irradiation. Irradiation of green fruit leads to reduction of the rate of subsequent carotenoid synthesis. In pink fruit the synthesis of carotenoids has already begun and radiation is without effect. In both green and pink fruit other disturbances of a physiological nature occur, leading to a susceptibility to infection of the tissue with microorganisms during storage. Hence irradiation of tomatoes is best used with fully ripe tomatoes and is therefore limited to control of microbial spoilage.

7.3.4. Vegetables

The principal interest in irradiating vegetables has related to the delay of senescence through sprout inhibition or similar processes which destroy the acceptability of these raw foods. Of major interest has been the irradiation of potatoes and onions. It has been established that irradiation is an effective means of keeping these foods for extended periods. Other foods, such as mushrooms, show promise of extension of life, but for shorter times.

A dose of 8 krad is apparently an optimum level for controlling the sprouting of white potatoes although the dose varies with the variety. Larger doses interfere with suberization (healing of injury) and can lead to increased rotting through microbial invasion of the tissue at locations of injury. The initial effect of radiation is to increase respiration. As shown in Figs 29 and 30, there is an initial rise in reducing sugar and a decrease in ascorbic acid. On storage, such differences from unirradiated potatoes disappear. Gamma radiation prevents internal sprouting as well as external. The use of stored irradiated potatoes for processing (e.g. chipping) is satisfactory but, based on a study with the Kennebec variety, problems may be found with extended storage (greater than eight months at 9°C), primarily due to non-enzymatic browning. It is important to store only potatoes of good initial quality, and varietal differences are important.

Onions respond to radiation somewhat similarily to potatoes. 4 to 8 krad appear a satisfactory dose range depending on variety. Discoloration of the interior of the bulb resulting from injury or death of the growing point has been observed. No off flavours have been detected, but a "mellowing" of the normal pungency has been reported. Again, varietal differences are important.

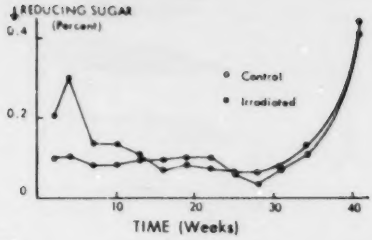

FIG. 29. Effect of storage on mean reducing sugar levels in Kennebec potatoes

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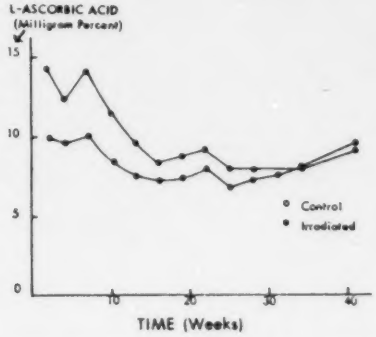

FIG. 30. Effect of storage on mean-L-ascorbic acid levels in Kennebec potatoes

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The inhibition of sprouting has been reported for red beets, turnips, ginger roots, sweet potato, Jerusalem artichoke tubers and carrots.

Mushrooms, in storage, desiccate and open their caps within five to seven days at 0-4°C. Irradiation of the Agaricus bisporus in the dose range 10 to 100 krad delays the cap opening for 10 to 14 days. The preservation effect of radiation is aided by appropriate packaging to lessen desiccation and gas exchange with the atmosphere.

7.3.5. Cereal grains, flour and baked goods

With cereals radiation appears to have its chief value in controlling insect infestations. Efforts to apply radiation to products made from cereal grains (other than flour) have not yielded particularly useful results.

The classes of insects of concern are moths, beetles, and mites. The dose required is somewhat related to the desired effect. If complete and immediate kill is required doses between 300 and 500 krad must be used. For complete kill within a few days 100 krad will suffice. For reproductive

sterilization 10 to 20 krad are sufficient. At 16 krad late pupae are able to produce adults, which are sterile and which die soon after emergence.

Doses up to 175 krad given to hard red winter wheat produced no immediate quality effects, nor any effects after storage for one year at 24°C as measured by common milling criteria. Breads made from the wheat at all levels of radiation were of good quality, but the 125 and 175 krad levels had a scorched odour while hot.

Control of fungi (moulds) on cereals by irradiation is not promising because of the high doses (ca. 200-400 krad) needed.

Little information exists on other grains. Only small effects on the malting properties of barley irradiated with up to 50 krad have been observed. 300 krad had no effect on the swelling process of corn. Except for a slight flavour change 50-100 krad had no effect on oats. Rice irradiated with doses up to 500 krad was satisfactory. Above this level it darkened and produced a gummy texture when boiled in water.

Flour made from wheat irradiated in the range of 20 to 150 krad shows increased starch viscosity and related parameters, possibly explaining an improvement in baking properties that has been noted for wheat so treated. Higher doses lead to an impairment of baking qualities.

Meager information suggests that, for many baked or prepared cereal products such as bread, cakes, biscuits, and macaroni, irradiated in the finished state, there exists a dose limit in the neighbourhood of 100 krad for them to be acceptable.

7.3.6. Eggs

The principal interest in the irradiation of eggs has been to remove the health hazard related to their Salmonellae content. The availability of heat treatment methods to solve this problem with eggs has substantially lessened this interest.

It has been observed that there are differences in the radiation resistance of strains of Salmonellae and that the resistance of a given strain varies with the nature of the egg product in which it resides. Table XIX shows data illustrating this variation for several serotypes of Salmonellae in different egg products.

It has been suggested that for Salmonellae an inactivation factor of 10^5 to 10^7 is required in eggs. Using the highest D_{10} value, 40.3 (for S. typhimurium (Table XIX), a dose of about 300 krad is indicated for liquid egg white.

The effect of irradiation temperature on the D_{10} value for S. typhimurium in whole egg is shown in Fig. 31. A sharp decrease in the D_{10} value occurs at about 45°C. It is probable that the temperatures above 45°C exert a significant bactericidal effect apart from that of the radiation and form the basis for the so-called combined treatment of heat and radiation.

Cakes baked from irradiated eggs tend to have a slightly reduced volume. The stability of the foam prepared from irradiated fresh and frozen egg white is somewhat less than that of comparable unirradiated products, but depends on the dose used.

Irradiation of shell eggs causes severe damage to the thick white, giving the egg an old appearance. Yolk membranes can be weakened or broken. Because of these effects irradiation of shell eggs has not been considered feasible.

TABLE XIX. THE EFFECT OF EGG PRODUCTS ON THE SENSITIVITY OF STRAINS OF SALMONELLA TO IRRADIATION WITH HIGH-VOLTAGE CATHODE RAYS (D_{10} (krad) when irradiated in)

Product	Serotype	State of product		
		Liquid	Frozen	Dried
Whole egg	S. typhimurium	40	-	55.7, 49.8
	S. senftenberg	17	-	60.5, 45.0
Yolk	S. typhimurium	-	42.7, 53.4	75.9, 66.5
	S. senftenberg	-	37.9, 48.6	80.6, 103
White	S. typhimurium	33.8, 40.3	35.6, 24.9	80.6, 86.5
	S. senftenberg	24.3, 30.8	16.0, 19.0	
White, sugared	Both			110, 130

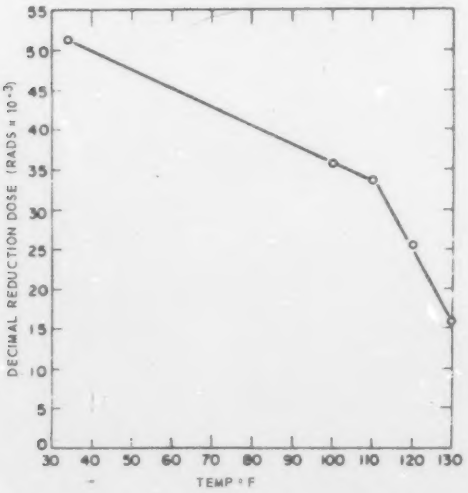

FIG. 31. Effect of irradiation temperature on the decimal reduction dose of S. typhimurium in whole egg

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7.4. Miscellaneous applications

Frozen horse meat, intended for use as pet food, is often found to contain Salmonellae. Based on D_{10} value of 128 krad for the most radiation-resistant strain, S. typhimurium, a dose of 640 krad has been proposed for this material.

TABLE XX. DOSES FOR SELECTED DEHYDRATED VEGETABLES AND FRUITS TO REDUCE COOKING TIME ON REHYDRATION

Product	Approximate preferred dose (Mrad)
White onion flakes	0.3
Tomato flakes	0.6
Potato dice	1.0
Carrot dice	2.0
Dried fresh peas	2.0
Leek	2.4
Bell pepper dice (green or red)	2.5
Cabbage flakes	3.0
Green lima beans	3.0
Celery flakes	3.3
Cut green beans	4.0
Okra pieces	4.0
Beet cubes	> 4.0
Apples	5.0
Prunes	9.0

Fresh French prunes irradiated with 400 krad or more, then dried, were found to be more tender than similar unirradiated dry prunes. Such irradiated prunes generally took up more water on reconstitution. This same amount of radiation shortened the freezing-drying of prunes by about one third. Blueberries irradiated with 300 krad lost 83% of their original weight in 30 hours as compared with 72% for unirradiated berries. Navy beans treated with 400 krad had the highest water uptake under a variety of rehydration conditions.

The softening effect of radiation has been considered as a means of reducing the cooking time for dehydrated vegetables in soups. Since different vegetables react differently to radiation, different doses are needed. In addition, different parts of a given vegetable react differently. Skins of lentils or of lima beans, for example, are preferentially softened and a more uniform texture of these foods is obtained through irradiation. With tomatoes, however, the skin is little affected compared with the flesh, causing an accentuation of the textural differences of these parts. The gum of okra, which accounts for a major characteristic of this vegetable, is destroyed by radiation.

Table XX lists the doses required for selected dehydrated fruits and vegetables to reduce the cooking time during rehydration from ten to twenty minutes to one or two minutes. Any deleterious effects on flavour or appearance are considered minor.

Low dose irradiation (300 - 1000 rad) of seeds and tubers such as potatoes and onions can lead to stimulation of the initial phases of growth and to an increase of crop yields.

Rye seeds treated with 700 rad in three days had a root diameter of 393 μm compared with unirradiated of 304 μm. The root length after four days was 52.2 mm compared with the unirradiated of 43.5 mm. Similar results have been observed for radishes, peas and cucumbers.

Increased yields have been observed as follows: radishes 30%, cabbage 19%, peas 16% and rye 21 - 22%.

8. PACKAGING

The purposes of packaging can be manifold, but the basic one is to protect the food from the environment. If the radiation treatment is intended to control microbial spoilage, then a very large aspect of this environmental protection is the prevention of recontamination of the food. In other cases the technical function of the package may be to prevent moisture loss, or to prevent moisture uptake, to provide an atmosphere other than air, to protect the food from mechanical damage or simply to keep it clean.

The packaging of irradiated foods is somewhat unusual in that in most cases the food can be packaged before treatment. Only low energy electrons or certain X-rays would present problems of penetration. Under proper conditions irradiation in the shipping or bulk container is possible.

The effects of radiation on the principal materials used in packaging are shown in Fig.32. This information suggests that irradiation can be used successfully with most conventional packaging materials. The following additional information on the classes of packaging materials can be a guide to their selection:

(a) Cellulose. This is a natural polymer having a high molecular weight and a crystalline character. In addition to natural cellulose, there are available a variety of cellulose derivatives such as cellophane, rayon and cellulose acetate. Irradiation causes chain degradation and other chemical changes, leading to decrease in molecular strength. The cellulose polymers are among the most radiation-sensitive packaging materials.

(b) Glass. In glass, irradiation produces free electrons, which may be trapped and cause the formation of colour-centres, at high doses this causes the (uncoloured) glass to turn brown. Heating the glass will restore the initial colourless condition. Radiation produces no other significant effect on glass.

(c) Metals. Radiation of the energy level employed in food irradiation increases the mobility of the outer-shell electrons of metals. This added energy ultimately degrades to heat, of negligible quantity. There is no other effect on metals.

(d) Organic polymers. Free radicals are formed in polymeric substances and these lead to cross linking or chain scission, or recombination. At the same time, hydrogen and other chemicals may be formed. If oxygen is present, oxidation may occur. The final result is determined by the predominant reaction, which is dependent upon the chemical structure of the polymer, the stress and environment. Radiation-induced changes can have a great effect on the physical properties of the polymer. Cross linking can increase tensile and flexural strength and

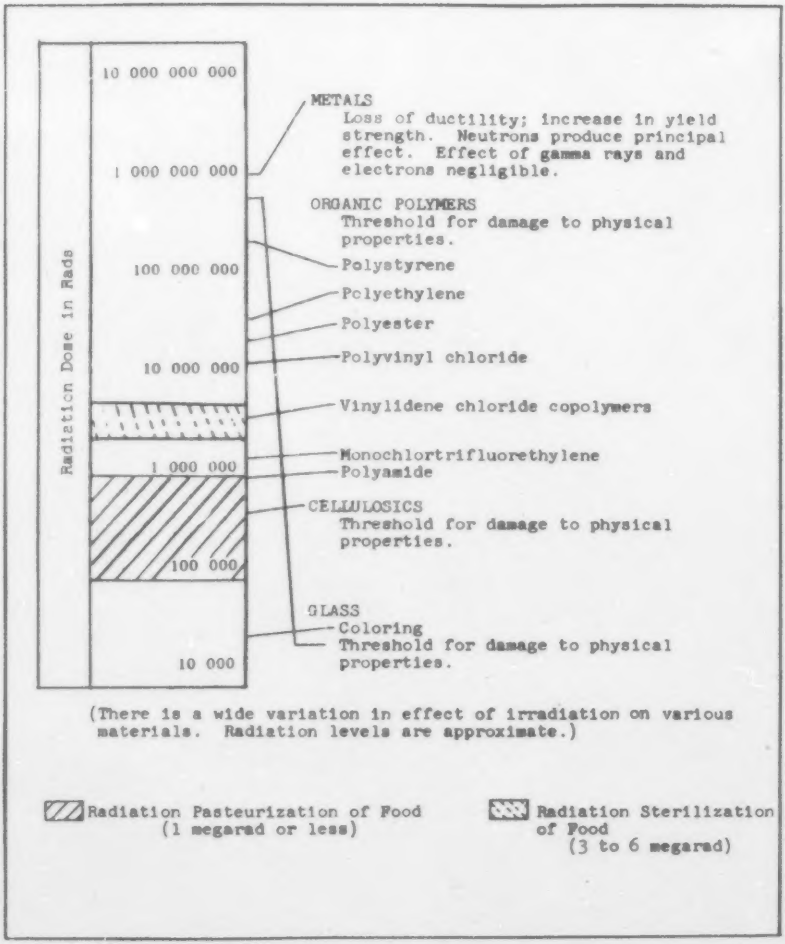
Radiation Dose in Rads
10 000 000 000
1 000 000 000
100 000 000
10 000 000
1 000 000
100 000
10 000
METALS
Loss of ductility; increase in yield strength. Neutrons produce principal effect. Effect of gamma rays and electrons negligible.
ORGANIC POLYMERS
Threshold for damage to physical properties.
Polystyrene
Polyethylene
Polyester
Polyvinyl chloride
Vinylidene chloride copolymers
Monochlortrifluorethylene
Polyamide
CELLULOSICS
Threshold for damage to physical properties.
GLASS
Coloring
Threshold for damage to physical properties.
(There is a wide variation in effect of irradiation on various materials. Radiation levels are approximate.)
Radiation Pasteurization of Food (1 megarad or less)
Radiation Sterilization of Food (3 to 6 megarad)

FIG. 32. Relative sensitivity to radiation of principal materials used in packaging

decrease elongation, crystallinity and solubility. Shortening of the polymeric chain through scission results in a decrease in tensile and flexural strength.

The choice of the packaging material and the nature of the container for a specific food are usually determined by the purpose which it is to serve. Sterilized foods must have a container which prevents access of bacteria and other microorganisms. This means a tightly closed container. Packages for low dose applications do not need to be tight.

Irradiation causes the formation of gases which can cause swelling of tight containers. Tables XXI and XXII show the results of analyses of

gases in the head space of various irradiation foods. Table XXIII gives similar data for model systems. The effect of radiation temperature on head-space composition is shown in Table XXIV. Since most flexible polymeric films are permeable to hydrogen, this gas disappears from packages made of such films on storage.

8.1. Rigid containers

The only rigid primary container for irradiated foods studied so far has been the metal can. Steel containers, tin plated and lined with an appropriate enamel, have proved satisfactory. Table XXV indicates the enamels found to be satisfactory for several foods.

Sulphur compounds from irradiated foods do not react with the metal surface of the can as readily as those from thermally processed foods. Irradiated foods, however, have marked dezincing properties and zinc oxide pigments should not be used in enamels.

Sealing compounds found to be satisfactory are those based on unvulcanized rubbers, including butadiene-styrene, butadiene-acrylonitrile and natural rubbers, neoprene and vulcanized rubber. Compounds based on butyl rubber are softened by radiation and cannot be used.

Aluminium cans are of interest because of their relatively low density and consequent smaller absorption of radiation. Such cans with appropriate enamels perform satisfactorily. The radiation-generated gas, however, can be a problem due to the relatively smaller physical strength of the aluminium can compared with that of the steel-based can. Because of the gas generation, some underfill of either type can is desirable.

Secondary rigid containers such as shipping or bulk containers made of fibre board (base material cellulose) suffer some loss of protective characteristics, but are generally satisfactory.

8.2. Flexible containers

Flexible plastic containers offer the means of saving weight and cube. In addition their low density makes them attractive for use with irradiated foods. Films thinner than 0.0254 mm have sufficient imperfections to preclude their use. Films 0.0254 to 0.0762 mm thick are proof against microorganisms; creasing of such films, however, will damage them sufficiently to make them unsatisfactory. Films over 0.0762 mm thick appear satisfactory.

The most satisfactory flexible package developed so far for radiation sterilized food employs a three-ply laminate made up as follows: 0.01270 mm Mylar A (outside), 0.01270 mm aluminium foil (middle) and a 0.0408 mm film of one of several types: (a) 0.0762 mm thick Nylon 11, or (b) 0.0762 mm thick high density polyethylene modified with isobutylene or (c) 0.0635 mm thick polyethylene polyester laminate. This lamination appears to provide the best performance based on the following criteria: the films are not changed adversely (a) in protective characteristics (e.g. heat stability, permeability, etc.), (b) by radiation-induced changes in the food, (c) to cause transmission of toxic or potentially toxic substances to the food.

TABLE XXI. HEADSPACE GAS IN CANNED FOODS IRRADIATED AT 4.5 Mrad
(can size: 307× 409; storage: 5-7 yr)

Product	Enzyme activity	Total gas (ml)	%						
			*N_2	O_2	H_2	CO_2	CO	CH_4	H_2S
Chili	Inactive	39.6	4.6	0	85.5	5.3	1.7	2.6	0
Cherries	Inactive	22.0	3.9	0	86	8.2	1.8	0	0
Green beans	Inactive	56.0	17.0	0	75.8	7.0	0	0.2	0
Ground beef	Active	80.0	32.9	1.3	29.3	31.0	2.2	3.2	0
Ground beef	Inactive	25.0	30.5	0.4	48.3	17.8	1.4	1.6	0

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TABLE XXII. HEADSPACE GAS IN WHOLE BONED HAM IRRADIATED AT 4.5 Mrad

Container	Storage time (months)	Total gas (ml)	%						
			N_2	O_2	H_2	CO_2	CO	CH_4	H_2S
Polyethylene bag	4	80	87.7	9.0	0	0	1.6	1.7	0
Polyethylene/foil laminate bag	4	40	81.0	2.0	0.01	0	11.6	5.4	0
No. 10 can	79	800	35.7	0	46.5	17.8	0	0.02	0

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TABLE XXIII. HEADSPACE GAS IN MODEL SYSTEMS REPRESENTING INDIVIDUAL FOOD COMPONENTS IRRADIATED AT 4.5 Mrad (can size: 303 × 406)

Model system	Total gas (ml)	%					
		N_2	O_2	H_2	CO_2	CO	CH_4
Water (distilled)	5.0	37.0	1.1	58.7	3.3	0	0
Water + 2% NaCl	5.5	29.4	0	68.6	2.0	0	0
Water + 10% sucrose	50.0	9.2	1.6	82.5	4.1	2.5	0
Water + 10% starch	50.0	16.2	2.5	78.5	1.1	1.6	0
Water + 10% dextrose	58.0	9.2	1.3	81.2	6.6	1.7	0
Water + 6% gelatin	40.0	8.4	0	65.1	0.3	22.8	3.4
Water + 10% corn oil	15.0	17.5	0	79.4	0.4	2.4	0.3
Sucrose (dry)	162	13.4	1.8	84.0	0	0	0
Starch (dry)	170	8.8	0	71.6	4.8	14.9	0
Dextrose (dry)	170	12.9	1.1	83.7	2.3	0	0
Gelatin (dry)	45	86.2	6.8	1.2	0.1	2.5	3.3
Oil (dry)	60	61.4	1.8	33.5	0	9.1	0.1

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TABLE XXIV. EFFECT OF IRRADIATION TEMPERATURE ON GAS PRODUCTION IN SUCROSE AND GELATIN SOLUTIONS IRRADIATED AT 4.5 Mrad
(can size: 303 × 406)

Irradiation temp. (°C)	Total headspace gas (ml)	
	10% sucrose solution	6% gelatin solution
20	58	35
5	62	32
-40	31	23
-80	29	23
-196	23	21
Control (unirrad.)	5	4

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Flexible packages for radiation pasteurized haddock fillets were found to be satisfactory when made from the following films:

Saran-coated nylon 11
Nylon 11
Polyolefin coated polyester
Semi-rigid polystyrene
Paper-aluminium-polyolefin coated polyester
Nylon-saran coated polyethylene
Aluminium coated nylon 11
Aluminium-paper polyolefin coated polyester
Polyethylene coated nylon
Nylon-saran-polyethylene

Films of polyethylene and polypropylene were not satisfactory.

For radiation pasteurized fresh meats the following oxygen-impermeable films appear satisfactory:

(a) Polyvinyl chloride (fresh meat wrap)
(b) Cellophane (fresh meat type)
(c) Polyethylene (high oxygen permeability type)

Among oxygen-impermeable films satisfactory for use with meats are:

(a) Polyvinylidine chloride
(b) A laminate of polyvinylidine chloride, polyester and polyethylene

Flexible packages for other irradiated foods have not been developed in any special way to date. It is likely that existing information as indicated above can be used as a guide.

TABLE XXV. CAN ENAMELS SATISFACTORY AFTER 12 MONTHS STORAGE AT 37°C

Product	Enamel	
	Best	Alternate
Cherries	Polybutadiene	Oleoresinous
Chili	Polybutadiene	Epoxy-phenolic
Beef	Polybutadiene	Epoxy-phenolic
Codfish	Epoxy-phenolic	Heat-reactive phenolic
Pork	Polybutadiene	Epoxy-phenolic

9. WHOLESOMENESS OF IRRADIATED FOODS

9.1. General considerations

It is generally accepted that no known hazard to health should be introduced in the utilization of irradiated foods. As with other methods of food preservation, irradiation can lead to certain biochemical and physical changes in the treated food. In order to determine whether such possible changes can create a health hazard to the consumer, it is important, therefore, to evaluate the food in terms of its safety.

For irradiated foods the following areas are considered pertinent for evaluation of safety:

(a) General toxicological considerations
(b) Carcinogenic considerations
(c) Mutagenic and cytotoxic considerations
(d) Nutritional considerations
(e) Microbiological considerations
(f) Considerations of induced radioactivity
(g) Packaging considerations

Some of these areas can be evaluated by chemical or physical methods. Information in other areas can be secured only by animal studies or by appropriate microbiological investigations.

9.2. General toxicological considerations

The complicated and incompletely understood chemical changes in foods resulting from irradiation do not allow identification of all chemical compounds which might be a health hazard. Subacute and chronic animal feeding tests are considered to be the only approach for detecting the presence, or absence, of dangerous compounds under these circumstances. Protocols for subacute tests have required the feeding of control

and irradiated foods to animals at approximately 35% of total dietary solids for 10% of their life span. The subacute test is considered to constitute a significant challenge to detect an abnormal physiological response. The chronic study is generally of two years duration and employs a larger animal population, usually with several species. Subacute and chronic studies yield information on growth, food efficiency, haematology, enzyme function, toxicity, urine analysis, gross pathology and histopathology. The chronic studies also measure reproduction, lactation and longevity.

The use of data from such animal feeding studies for accepting foods for human consumption represents an extrapolation from other species to the human. Since it is not possible to conduct comparable studies with humans there is no alternative but to employ such extrapolation. The absence of a toxic or carcinogenic effect in a well-designed animal feeding study can provide a reasonable basis for confidence that no problem will arise through consumption of the food by man.

9.3. Carcinogenic considerations

Carcinogenic studies are likewise made with animals. It is customary to feed animals having demonstrated a strong proclivity towards cancer development. Rats and mice are particularly convenient species for studies in this area.

9.4. Mutagenic and cytotoxic considerations

It has been reported that the irradiation of at least one food component, sucrose, leads to the formation of a compound(s) capable of causing chromosomal aberrations in isolated carrot cells. Gene mutations have been observed on Drosophila raised in media containing irradiated glucose. These observations suggest that irradiated foods might cause similar effects with other organisms, but the view has been expressed that it has not been established that they are relevant to mammalian animals, since the compounds in question may be destroyed or prevented from reaching the critical organs by the action of the regular body processes. No mutagenic effect has been proven thus far in mammals. There appears to be no simple or inexpensive approach to the evaluation of irradiated foods for potential mutagenic or cytotoxic effects.

9.5. Nutritional considerations

Nutritional quality of irradiated foods can be assessed by taking into account the following:

(a) Vitamin content, stability and physiological availability
(b) Fat content, quality and essential fatty acid composition
(c) Protein quality
(d) Digestibility of fat, carbohydrate, and protein components of the food, and the availability of the potential biological energy derived from them
(e) The absence of anti-metabolites
(f) The subjective qualities of food that make it desirable to eat

Some of these factors can be evaluated through chemical analyses. The best way to evaluate all nutritional components collectively is through an animal feeding study measuring items such as growth, reproduction, food consumption and efficiency and the occurrence of gross abnormalities.

9.6. Microbiological considerations

The area of concern for the microbiological aspects of irradiated foods will vary with the kind of treatment involved. For sterilized products, the dose must be adequate to destroy or inactivate all spoilage microorganisms. For non-acid foods with high water content and which allow germination of the spores of Cl. botulinum the dose must be sufficient to accomplish a reduction of the spore count by 10^{12} (that is, by 12 D_{10}). As has been noted, this calls for 4.5 Mrad for Cl. botulinum Type A, the most radiation-resistant type. In order to be absolutely safe on this important consideration, an "inoculated pack study" is generally employed. In this technique the food in question is inoculated with appropriate levels of the spores of Cl. botulinum, processed (including irradiation at several levels) and stored under conditions which will allow spore germination. Correlation of growth and toxin formation with radiation dose is made and the minimum dose requirement established.

For products irradiated with a less than sterilizing dose and for which there occurs a microbial spoilage ultimately, there are other important microbiological considerations. The radiation may eliminate or inhibit the normal outgrowth of the usual flora, leading to a different microbial spoilage pattern. This new pattern must be identified and evaluated to determine if it occasions a possible health hazard to the consumer of the food. The new outgrowth could include substantial numbers of a particular organism, which is usually suppressed by the flora normal to the unirradiated food.

9.7. Considerations of induced radioactivity

There is general acceptance to the view that any added radioactivity is undesirable and is not to be permitted. For this reason, as discussed under 1.5.5., the only radiation sources that are permitted are ^{60}Co, ^{137}Cs, up to 10 MeV accelerated electrons, and X-rays from a source producing a beam of an energy not higher than 5 MeV. All these sources have energy levels below that necessary to induce radioactivity in elements contained in foods.

9.8. Packaging considerations

The basic consideration of packaging in terms of wholesomeness is the transfer from the package to the food of any material capable of causing a health hazard to the consumer. A secondary consideration is the ability of the package to protect the food from the environment. These same considerations apply to any package used for food. The only new requirement is the effect of radiation on the food or on the material from which the package is made.

TABLE XXVI. SUB-ACUTE TOXICITY STUDIES
(Rat feeding - 8 weeks; 0, 2.79 and 5.58 Mrad)

Meats	Fish	Cereals	Fruits	Vegetables	Desserts and other
Beef, corned	Crab[b, c]	Bread	Apples[b, c]	Asparagus	Dessert powder (vanila)
Bacon	Flounder[b, c]	Cereal bar	Apricots, dried	Beets	Gelatin dessert powder
Beef	Haddock[a, c]	Crackers	Apricots, fresh[b, c]	Brussels sprouts	Nut roll
Chicken[a, c]	Salmon	Macaroni	Cherries, sour	Cabbage	Peanut butter
Frankfurters	Shrimp[a, c]	Rice	Cherries, sweet[b, c]	Carrots	Pound cake
Ham	Soft shell clams[b, c]		Melon	Cauliflower	Whole dried milk
Sausage	Tuna		Peaches	Celery	
Turkey			Pears, dried	Corn	
			Pears, fresh[b, c]	Cranberries	
			Prune plums[b, c]	Green beans	
			Raisins	Green peas	
			Strawberries[a, c]	Lima beans	
				Mushrooms	
				Onions[b, c]	
				Potatoes, white	
				Potatoes, sweet	
				Spinach	

[a] Also 300 krad
[b] 300 krad
[c] Rats and dogs fed

TABLE XXVII. LONG-TERM TOXICITY STUDIES
(Rat and dog feeding - 2 years; 0, 2.79 and 5.88 Mrad)

Meats	Fish	Fruits	Vegetables	Other
Bacon	Cod	Bananas[g]	Carrots	Flour[c]
Beef	Shrimp	Compote (dried mixture)	Cabbage	Jam
Beef stew	Soft shell clams[f]	Peaches[a]	Corn	Milk, evaporated
Chicken	Tuna	Oranges[a, d]	Green beans	
Chicken stew		Strawberries[e]	Potatoes, white[b]	
Lamb[h]			Potatoes, sweet	
Pork loin				

[a] Fed to rats and monkeys
[b] Doses of 7 and 40 krad
[c] Doses of 37 and 74 krad
[d] Doses of 140 and 280 krad
[e] Doses of 150 and 300 krad
[f] Doses of 400 and 800 krad
[g] Doses of 20 and 40 krad
[h] Pasteurizing dose

9.9. Research on wholesomeness

A great deal of effort has been extended on wholesomeness studies, and much work is continuing. For the present there appears to be a necessity to establish the safety of each food through separate studies. The following foods shown in Tables XXVI and XXVII are reported to have been or are being studied.

While the work completed so far is being subjected to evaluation and possibly to extension, it is clear that irradiation does not produce any obviously toxic or carcinogenic substances in the foods that have been tested. Some loss of nutrients has been reported but this is generally dose dependent and for sterilized products is comparable with that obtained with heat processing. Some small but measurable decreases in digestion rates have been observed but are not biologically significant. While the possibility of toxicity at the cellular level and mutagenicity cannot be dismissed easily, the questionable relevancy of data obtained with tissue cultures and Drosophila to mammals plus the voluminous negative data obtained with mammals, suggest that the toxicity of irradiated foods must be extremely subtle or of such a low frequency rate that it is very difficult to demonstrate experimentally. Improved techniques of evaluation may help in this situation but for the present the evidence appears to indicate that irradiated foods are wholesome.

The question of induced radioactivity is resolvable on the basis of proper control of the radiation. This solution of the potential problem of induced radioactivity has been arrived at through a study which included

(a) the irradiation of elements in foods expected to produce radioactive products through low-energy-requiring isomer-activation (γ, γ' reaction and the higher-energy-requiring particle-emission reaction), (b) the irradiation of foods enriched with these elements, and (c) the irradiation of unenriched foods. Sources employed were ^{137}Cs, ^{60}Co, spent fuel rods, and electrons and X-rays with energies of 4 to 25 MeV.

From these studies it was determined that:

(a) Induced isomer activity is experimentally undetectable in foods. The calculated radioactivities of ^{117}Sn and ^{119}Sn in foods irradiated with 24 MeV X-rays are at least one order below the natural ^{3}H radioactivity.

(b) In beef irradiated with 24 MeV electrons, it was calculated that nine radionuclides with half-lives of more than 10 days could be found. Of these, seven could be detected only if the food element was enriched before irradiation or concentrated after irradiation. Only two elements, ^{22}Na and ^{84}Rb, could be detected directly. Of the several samples of beef tested in the various phases of this study, ^{84}Rb was found in only one sample.

(c) In a study where six foods and a composite diet were irradiated to 5 Mrad with electrons, only one induced radionuclide (^{24}Na) was detected at energies less than 12 MeV. The short-lived ^{24}Na was detected at 12 MeV in ham, chicken, and shrimp and at 10 MeV in the composite diet. The long-lived ^{22}Na was detected at energies greater than 14 MeV. At 14 MeV, the ^{24}Na and ^{22}Na produced were present at concentrations of 10^{-3} and 10^{-5}, respectively, below the maximum permissible concentration in water. No beta emitters were detected.

(d) Studies showed no detectable induced radioactivity in foods irradiated with ^{60}Co or electron beams of less than 11.2 MeV. At energies between 12-16 MeV, six gamma emitters and one beta emitter (^{32}P) were detected.

From these investigations, it was concluded that there is no detectable induced radioactivity in foods irradiated with electron beams of less than 10 MeV. Of the nine radionuclides identified and detected at energies greater than 11.2 MeV, only five had half-lives of more than 10 days, ^{54}Mn, ^{22}Na, ^{84}Rb, ^{46}Sc and ^{32}P.

To illustrate the magnitude of induced radioactivity in foods, it was calculated that the body burden of ingesting 100% of one's diet of 24 MeV electron irradiated food would be 0.26 mR/year. This includes all radioactive elements produced whether or not they are detectable. (This figure of 0.26 mR/year is probably a high estimate since most of the calculated values based on enriched samples tended to be high by at least a factor of 2). The body burden and external irradiation from natural sources has been estimated to be about 150 mR/year of which 5 mR is contributed by fallout products.

Stating the situation another way, at 24 MeV, electron irradiated food has a less than 5% increase of the natural radioactivity. This is insignificant compared with the possible ten-fold increase in activity obtained from the use of certain food additives and condiments (which contain ^{40}K).

The significance of the statement "no detectable activity" can be appreciated further when one considers that the gamma counters used can detect 0.001 pCi/gram of food or, in other words, several nuclei out of 10^{25}.

Present views are that gamma radiation with energies up to 5 MeV and electrons with energies up to 10 MeV produce no detectable induced radioactivity in foods and, therefore, are safe to use for food irradiation.

10. GOVERNMENT REGULATION OF IRRADIATED FOODS

In order to give the consumer protection against health hazards from consumption of irradiated foods or against false representation of what he is purchasing, it is generally agreed that governments should regulate the manufacture, storage and distribution of irradiated foods. Where consumer concern exists, such regulation in addition will provide the consumer with a basis for using irradiated foods with confidence.

A common approach by countries to legislation will aid international trade in irradiated foods.

10.1. Procedures and requirements for clearance for human consumption

Some countries have approached the procedure for regulation of irradiated foods by way of a general prohibition which can be removed when the requirements for such action are satisfactorily met. Thus it is possible to control the irradiation of each and every food.

The requirements to be met have included the considerations given in section 9.1.

10.2. Regulations for control of manufacture, labelling and distribution

It is considered likely that each irradiation facility will need to be licensed or otherwise regulated to provide the needed control to assure a safe operation. Concern for safety involves personnel operating the facility and for operating procedures with regard to the processed foods. Personnel safety measures are well established and easily provided for. The control of the process with respect to the foods is likely to include (a) dosimetry and control of dose; (b) avoidance of contamination of the food with radioactivity (from the source); and (c) plant sanitation and related items of food handling.

In some countries the labelling of the food as having been treated with ionizing radiation will be required. This is intended primarily to advise the purchaser of the treatment. In some cases labelling may serve the function of preventing more than one irradiation of a given lot of food. An example of this kind of situation would be the limitation of the irradiation of wheat for disinfestation purposes to a single treatment.

Distribution of irradiated foods within a country presents no problems different from those with other foods. If irradiated foods become items of international trade, then the ordinary problems of production, exportation and importation will occur. Because of the newness of irradiation, in many instances there probably will not exist regulations covering these foods. This circumstance points to the need of international agreements on regulations for irradiated foods.

11. FOOD IRRADIATION FACILITIES

11.1. Radiation characteristics

The only types of ionizing radiation of interest for food irradiation are gamma, electron, X-ray, and possibly beta. The choice of one of these for a particular application will be governed by various factors, but all such factors can be reduced to two general considerations: (1) within allowable energy level the radiation limits must be capable of reaching all those parts of the food which are required by the process and (2) economic considerations.

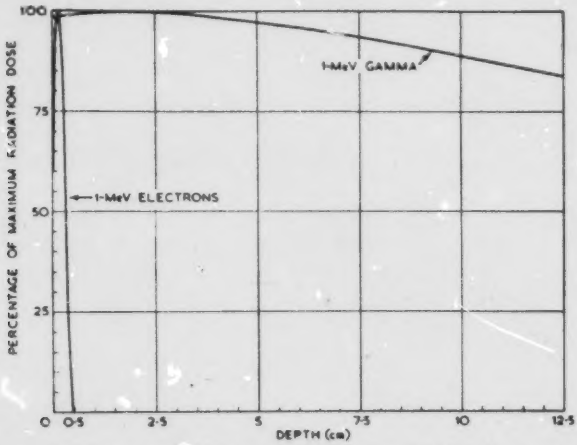


FIG. 33. Comparison of depths of penetration of 1 MeV electrons and 1 MeV gamma rays in water

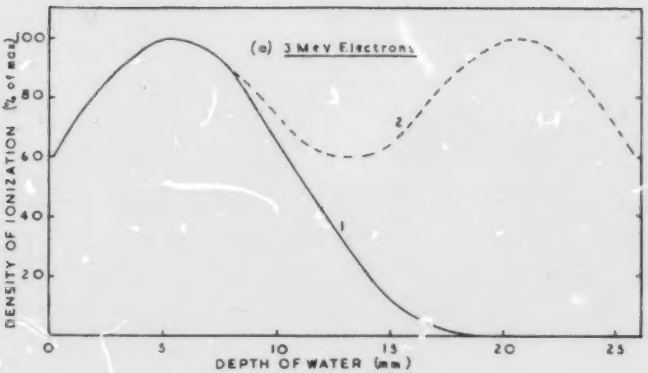
There are differences in penetration of the various types of radiation, making this an important factor of selection. Figures 33, 34 and 35 indicate the penetration for beta, gamma and electron radiations. Recalling that 10 MeV limit exists for electrons, even with two sided irradiation electrons cannot penetrate more than about 7 cm of unit-density material. ^{90}Sr beta ray loses 50% of its intensity in the first millimetre. One MeV gamma rays, on the other hand, can penetrate about 20 cm of water before losing 50% of their intensity.

The variation in absorbed dose is important from many aspects. Any dose greater than the minimum is wasted energy and contributes to the inefficiency of the irradiator. On the other hand, a limitation of a narrow range between maximum and minimum dose may make it difficult to capture some of the radiation in the target material.

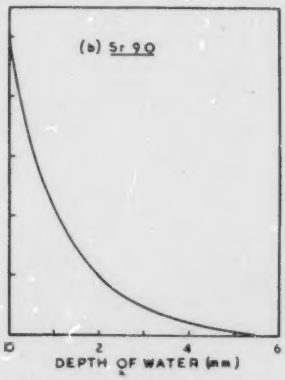
It should be recognized that obtaining the minimum dose specified is more critical in the case of sterilization applications than in other kinds.

11.2. Selection and fabrication of isotopic sources

Isotopic sources so far have been made either of ^{60}Co or ^{137}Cs. The radiation characteristics of these isotopes are given in Table XXVIII. ^{60}Co



(a) From 3 MeV Van de Graaff generator
1. Irradiated from one side
2. Irradiated from two opposite sides



(b) From source of Strontium 90, 7 mm diameter, on surface of water

FIG. 34. Density of ionization at various depths in water irradiated with high energy electrons

sources are made of the metal in various sizes and shapes, including strips, rod and helically coiled wire. To avoid contamination of the environment, the cobalt is doubly encapsulated in stainless steel. ^{137}Cs is usually supplied as CsCl pellets and also is doubly encapsulated in stainless steel. In order to provide a source for a particular installation the individual strips or other forms are assembled into an appropriate configuration such as a placque or cylinder made up of pencils or rods of the isotope. By incorporating the requisite number of rods or pencils a source of a desired radiation output is secured.

11.3. Research facilities

A number of facilities for research on food irradiation have been built and installed in government, university and private laboratories. Most such facilities employ ^{60}Co. A few have ^{137}Cs and still others have machine

sources of radiation. The shielding problem has been solved in two principal ways: (1) the use of a sufficient depth of water and (2) the use of a solid absorber such as lead or concrete. In most large radioisotope sources the combination of water and solid shielding has been used. The isotopic source is stored in a water pool when not in use and raised into position in air for use. While raised, the shielding is accomplished with the solid shielding.

Figure 36 shows a schematic diagram of a water-shielded ^{60}Co research irradiator. In this type 32 000 Ci of ^{60}Co were employed. The products for irradiation, up to a size 35 × 45 × 15 cm are placed in water-tight containers and lowered to the source, which is kept at the bottom of the pool.

Figure 37 is an example of a source in which the ^{60}Co is raised for use. Since it is not necessary to submerge the samples in the water, this arrangement is more convenient. While the source is at the bottom of the

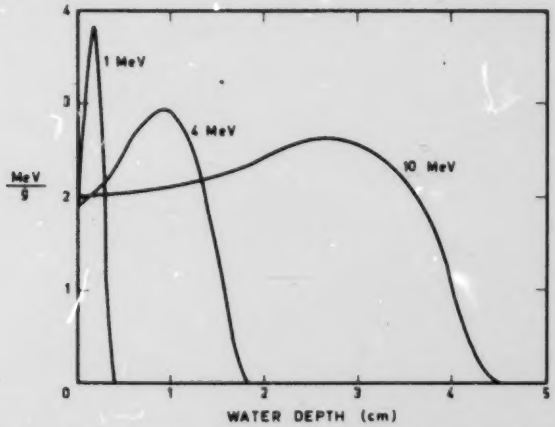


FIG. 35. Depth dose curves for a plane-parallel electron beam incident normally on water with 1 electron per cm²

TABLE XXVIII. CHARACTERISTICS OF ^{60}Co AND ^{137}Cs

	^{60}Co	^{137}Cs
Typical source form	metal	CsCl pellets
Half-life	5.3 yr	30 yr
Available specific activity	1 to 400 Ci/g	1-25 Ci/g
Gamma energy	1.17, 1.33 MeV	0.66 MeV
Power	65 Ci/W	207 Ci/W

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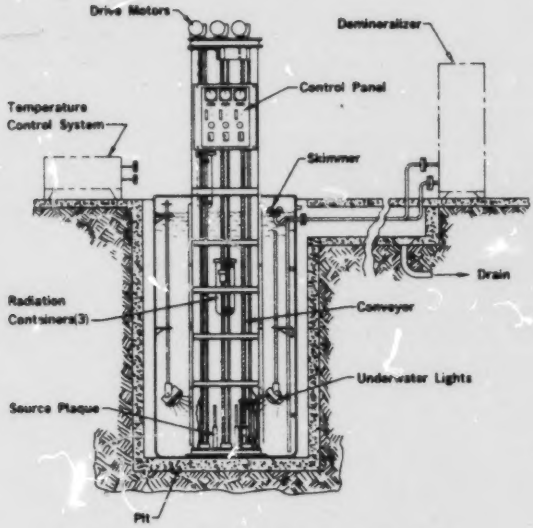
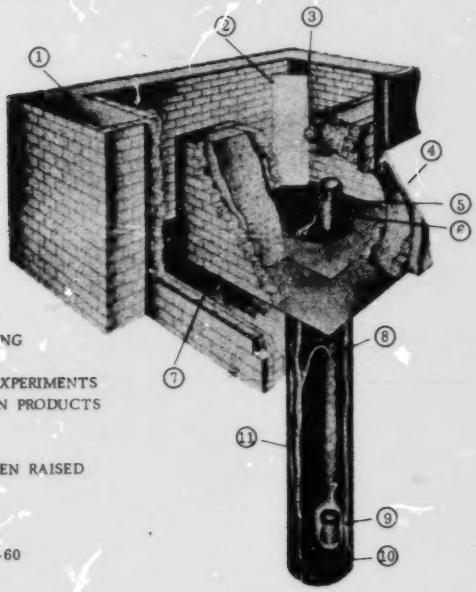


FIG. 36. Water-shielded ^{60}Co research irradiator



1 1,22 m CONCRETE SHIELDING
2 MIRROR
3 "CAVE" FOR RADIATION EXPERIMENTS
4 SECOND FLOOR OF FISSION PRODUCTS LABORATORY
5 WIRE MESH CAP
6 POSITION OF SOURCE WHEN RAISED
7 LABYRINTH ENTRANCE
8 ELEVATOR GUIDES
9 WELL-4,88 m DEEP
10 10000 CURIES OF COBALT-60
11 ELEVATOR

FIG. 37. University of Michigan ^{60}Co irradiation cave

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pool, samples for irradiation are taken into a cave made of shielding material (e. g. concrete) which is built over the pool; the samples are located a specific and appropriate distance from the source. Personnel then leave the cave, and, by remote operation the source is brought out of the water. On completion of the irradiation it is lowered into the water.

To provide for a continuous operation, some facilities have included a carrier system which transports product from outside the shielding to the source and back outside again. Such a facility is shown in Fig. 38.

A simple portable gamma source employing lead shielding is shown in Fig. 39. A source of this type can contain as many as 24 000 Ci of ^{60}Co. Some truck-mounted portable irradiators have been built, containing either ^{60}Co or ^{137}Cs. One such irradiator is shown in Fig. 40.

Machine sources can be used in research on food irradiation in much the same way as isotopic sources. Figure 41 shows a linear accelerator installation.

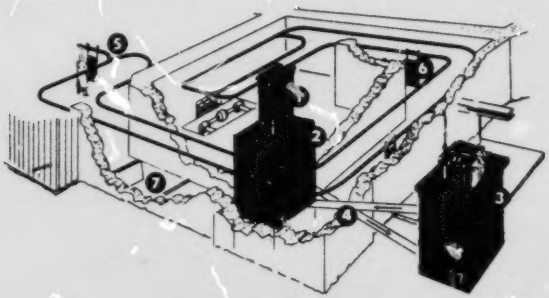

FIG. 38. Gammacell: 1 cobalt source (elev.); 2 Inner pool; 3 Cask pool; 4 Transfer tubes; 5 Overhead conveyer; 6 Trays; 7 Man trap (United States Army Food Radiation Laboratory, Natick, Mass.).

11.4. Production facilities

While a number of designs have been prepared for production plants for the irradiation of foods, only a few facilities have actually been built. Figure 42 shows one built in Canada for the irradiation of potatoes. This unit had a capability of containing 600 000 Ci of ^{60}Co and can handle 40 boxes of potatoes per hour. The minimum dose is 5 to 6 krad with a maximum non-uniformity of 2.25/1.00. The boxes are 1.2 m on a side and receive radiation on four sides.

Figure 43 shows an industrial radiation facility at Dagneux, France. It is designed to use a "panel" or placque source of up to 300 000 Ci of ^{60}Co. The panel is made up of standard cylindrical elements, each of approximately 1000 Ci. A continuous conveyor system carries baskets from outside into irradiation chamber and out again. The baskets are turned 180° as they pass from one face to the other of the panel source. Baskets can hold up to 50 kg and have dimensions of 28 × 28 × 116 cm. The speed of the conveyor is variable between 0.012 and 0.075 m per minute. When not in use the source is stored in a water pool.

The Package Irradiation Plant at Wantage, United Kingdom, is shown schematically in Fig. 44. Its ^{60}Co source is reported as 300 000 Ci. It

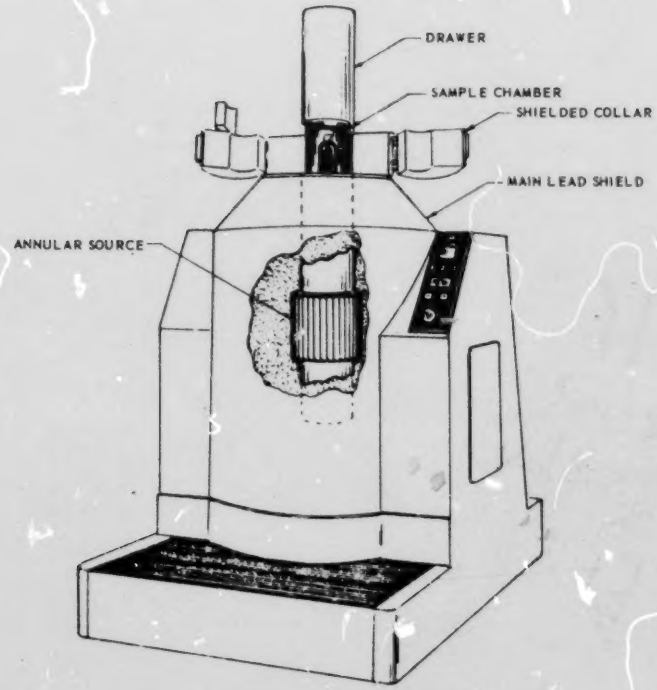

FIG. 39. Lead shielded gamma cell

will accept packages 34 × 29 × 22 cm. It can run automatically continuously without supervision. The conveyor input and output stores each will handle up to 3200 packages, a feature which permits unattended operation for a several day period.

A number of irradiation facilities exist for purposes other than food treatment. Figure 45 shows a facility designed for the sterilization of medical supplies. Figure 46 portrays an irradiator for sterilizing goat hair.

It will be noted that the industrial facilities for both food and other materials referred to above employ ^{60}Co. There are, however, a number of machine sources used in industrial applications, primarily radiation-induced chemical changes in polymers. These non-food applications are providing a basis of industrial experience for facility design and operation for food irradiation.

12. COMMERCIAL CONSIDERATIONS OF FOOD IRRADIATION

Regardless of how business is conducted in a given country, in order for irradiation to be used as a food preservation or improvement process, it must serve a useful purpose. Particular ways in which irradiation can

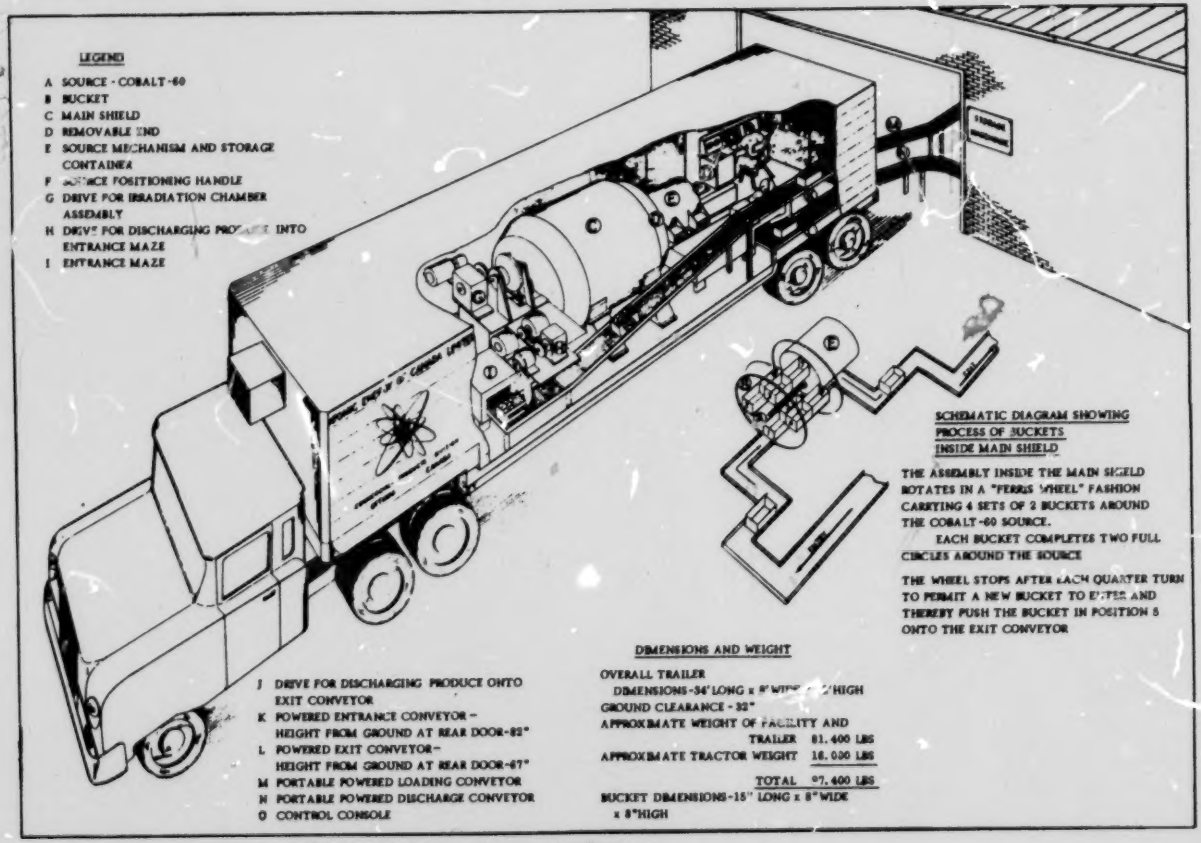
LEGEND
A SOURCE - COBALT-60
B BUCKET
C MAIN SHIELD
D REMOVABLE END
E SOURCE MECHANISM AND STORAGE CONTAINER
F SOURCE POSITIONING HANDLE
G DRIVE FOR IRRADIATION CHAMBER ASSEMBLY
H DRIVE FOR DISCHARGING PRODUCE INTO ENTRANCE MAZE
I ENTRANCE MAZE
J DRIVE FOR DISCHARGING PRODUCE ONTO EXIT CONVEYOR
K POWERED ENTRANCE CONVEYOR - HEIGHT FROM GROUND AT REAR DOOR-82"
L POWERED EXIT CONVEYOR - HEIGHT FROM GROUND AT REAR DOOR-67"
M PORTABLE POWERED LOADING CONVEYOR
N PORTABLE POWERED DISCHARGE CONVEYOR
O CONTROL CONSOLE
DIMENSIONS AND WEIGHT
OVERALL TRAILER DIMENSIONS-34' LONG x 8' WIDE x 12'HIGH
GROUND CLEARANCE - 32"
APPROXIMATE WEIGHT OF FACILITY AND TRAILER 81,400 LBS
APPROXIMATE TRACTOR WEIGHT 16,000 LBS
TOTAL 97,400 LBS
BUCKET DIMENSIONS-15" LONG x 8" WIDE x 8"HIGH
SCHEMATIC DIAGRAM SHOWING PROCESS OF BUCKETS INSIDE MAIN SHIELD
THE ASSEMBLY INSIDE THE MAIN SHIELD ROTATES IN A "FERRIS WHEEL" FASHION CARRYING 4 SETS OF 2 BUCKETS AROUND THE COBALT-60 SOURCE.
EACH BUCKET COMPLETES TWO FULL CIRCLES AROUND THE SOURCE
THE WHEEL STOPS AFTER EACH QUARTER TURN TO PERMIT A NEW BUCKET TO ENTER AND THEREBY PUSH THE BUCKET IN POSITION 5 ONTO THE EXIT CONVEYOR

FIG. 40. Truck-mounted gamma irradiator

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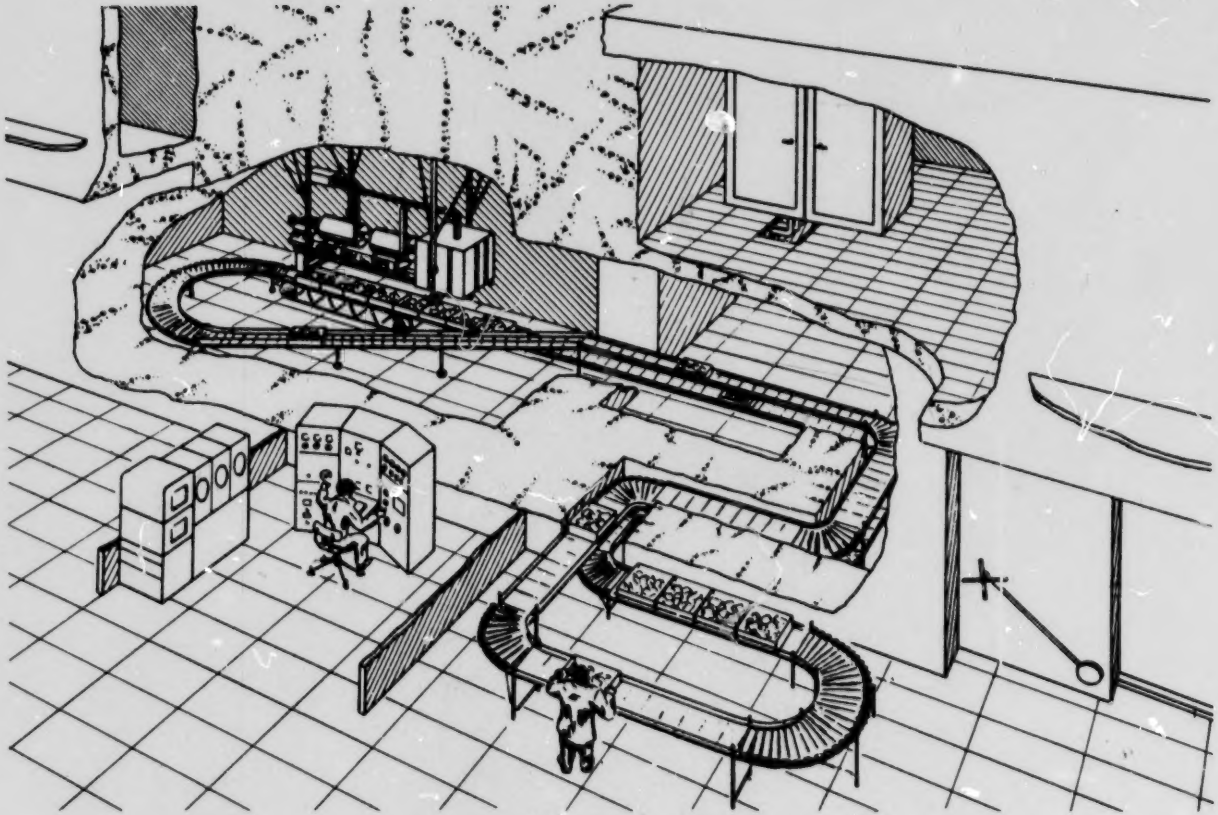

FIG. 41. 15-MeV linear accelerator at Risø, Denmark

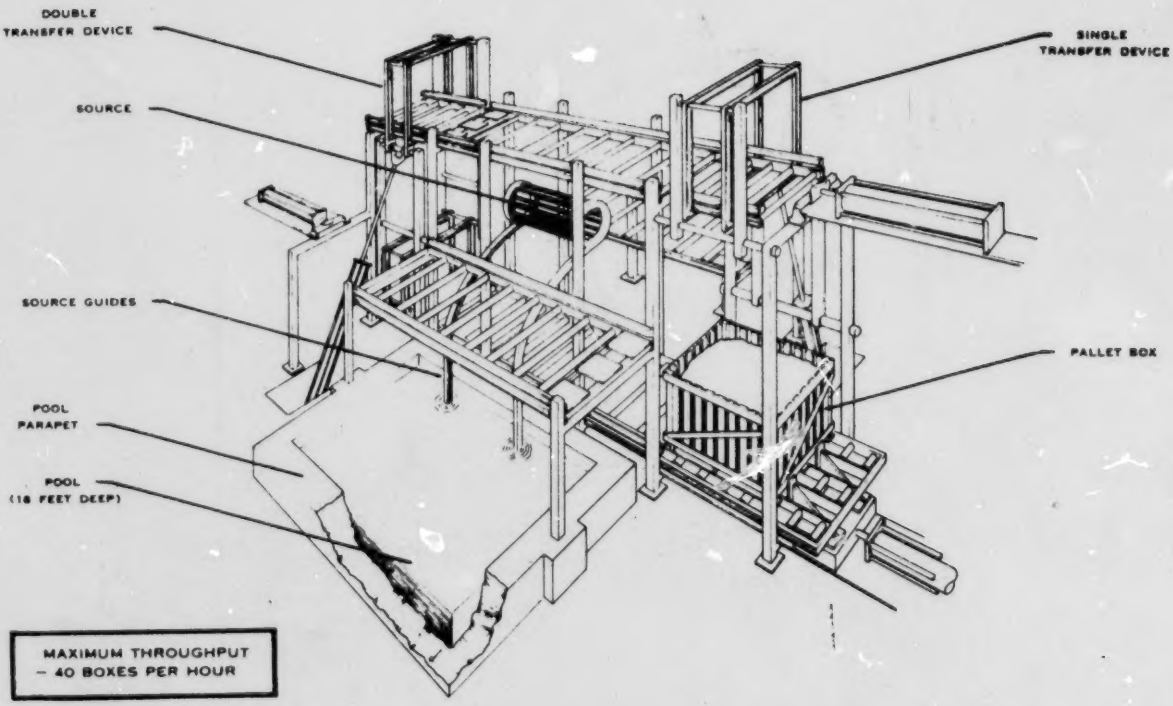

FIG. 42. Canadian potato irradiator

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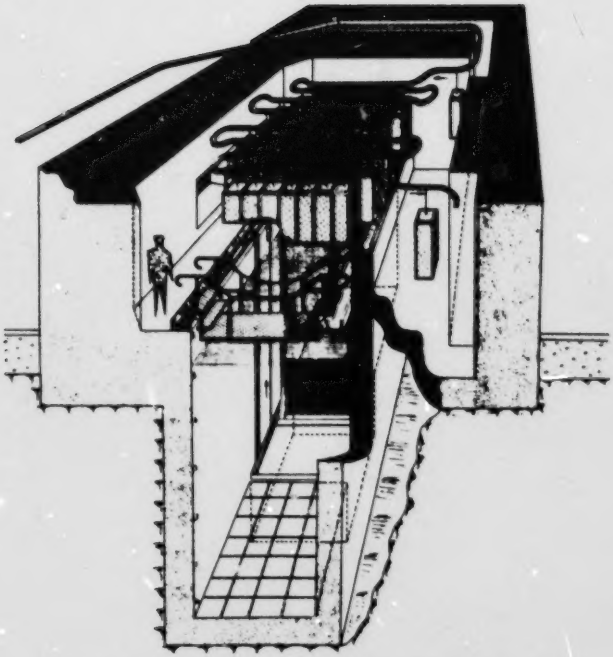


FIG. 43. Basket conveyor system irradiator – Dagneux, France

be useful were described (see section 7). The fitting of these methods of usage into a country's food preservation and distribution system will vary greatly with local conditions, and it is difficult to give specific information on how this is to be done. One can, however, identify certain steps which will apply generally:

(a) Development of the technology of product and process
(b) Government approval for the necessary packaging of the product, and process, including regulations therefore
(c) Pilot scale production in order to develop a process suitable for for commercial scale and to test the acceptance of the product in the market place. This will include determination of cost and determination of cost acceptance by consumer
(d) Assuming a favourable situation as determined in (c), production and distribution are increased to supply the irradiated food under the best attainable economies in competition with other foods on a broad market basis.

The consumer is the ultimate judge of the value of the product. His willingness to use it and to pay for it determines the commercial success of a product. In some cases, irradiated foods will find their justification in better quality or reduction of a health hazard; in others, there will be no product improvement, but the advantage will be one of reduced cost. One or the other, or a combination of these, will form the basis of the consumer's use of the irradiated food.

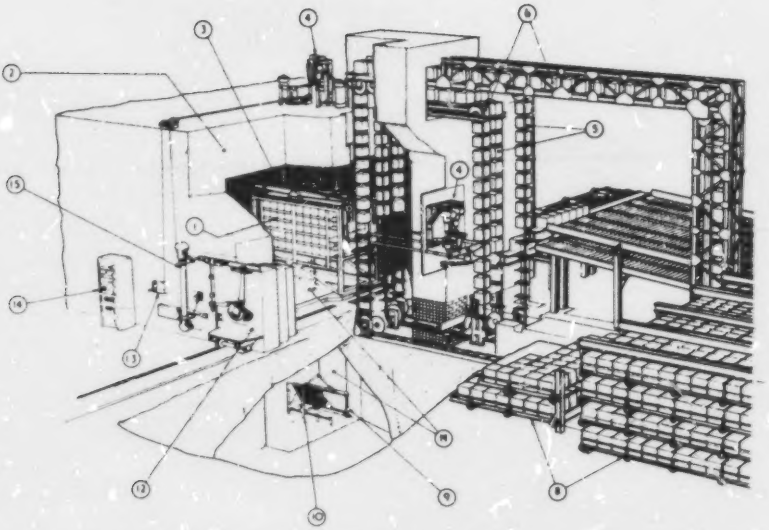


FIG. 44. The package irradiation plant at Wantage research laboratory

1 Irradiation machine
2 Concrete radiation shield
3 Radiation source (working position)
4 Irradiation machine hydraulic mechanism
5 Output transfer conveyors
6 Input transfer conveyors
7 Post-treatment storage rack
8 Pre-treatment storage rack
9 Radiation source-in frame (storage position)
10 Source loading jig
11 Water pond (for shielded source storage)
12 Plug door (interlocked with source position)
13 Source hoist control valve
14 Main control panel
15 Source hoist cylinder

12.1. Consumer acceptance of irradiated foods

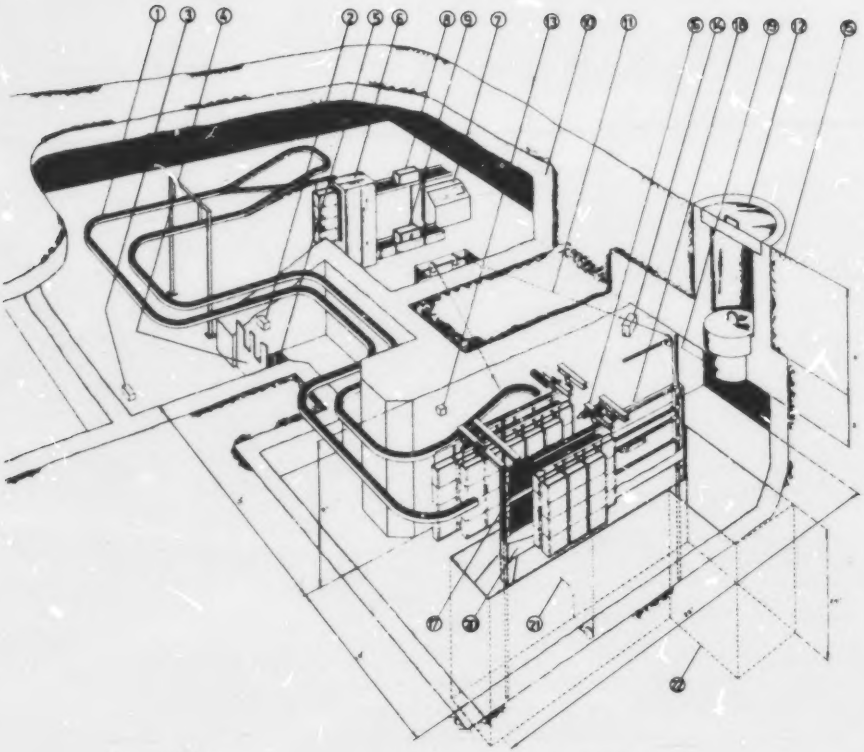
There are at least three aspects of consumer acceptance of irradiated foods which can be identified:

(a) The broad one of having concern over the fact that the foods have been treated with radiation

(b) The acceptance of those foods which are identical in quality with unirradiated counterparts as far as the consumer can determine

(c) The acceptance of those foods which as a consequence of irradiation have some kind of quality improvement.

The first aspect has itself several facets. There is the basic one of the actual consumer's acceptance of irradiation. In addition to the consumers are the food manufacturers and distributors, who have concern for the consumer's reaction, and for the risks they undertake in the manufacture and sale of irradiated foods because of uncertainty about consumer acceptance. Finally there are the government regulatory agencies, whose judgment of the safety of irradiated foods for human consumption allows such foods to be distributed to the public. Their responsibility in arriving at this judgment is a weighty one and their action must have the ability to convince the consuming public that there is no hazard.



LEGEND

1 CONVEYOR
2 MAZE MONITOR
3 MONITOR
4 DOOR
5 DEAD MAN PLATE
6 LOAD-UNLOAD STATION WITH PRODUCE MONITOR
7 CONTROL STATION
8 INPUT
9 OUTPUT
10 STANDARD DENSITY CONCRETE SHIELD
11 STAINLESS STEEL HOIST CABLE
12 SOURCE FLASK ENTRY HATCH
13 MONITOR
14 T. V. CAMERA
15 GROUND LEVEL
16 PNEUMATIC HORIZONTAL TRANSFER POINT
17 COBALT 60 SOURCE PENCILS
18 SOURCE RACK
19 REMOVABLE SHIELD
20 ALUMINIUM SOURCE GUARD
21 SOURCE
22 STORAGE POOL

FIG. 45. ^{60}Co irradiator for medical supplies

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Many irradiated foods will not be changed from their ordinary character as a consequence of being irradiated, and the consumer will see no difference from what he has been accustomed to. Foods irradiated for insect infestation control, or delay of senescence, will have normal characteristics. These the consumer should accept without difficulty, provided the first aspect presents no problem and provided cost is satisfactory.

For irradiated foods having a quality improvement there should be increased consumer acceptance. Just how much extra cost can be justified will vary with many circumstances. It is likely that answers in this area can be obtained only when irradiated foods are distributed in competition with other foods.

Concern has been expressed about damage to product quality by radiation. As noted earlier, this can happen. For some foods this will so reduce consumer acceptance as to prevent application of irradiation to such foods. For others there is no detectable difference, and there will be no quality problem. For still others there is a detectable difference in quality and the question is how much change will be tolerated, especially if viewed in terms of an advantage gained (e.g. availability through product life extension).

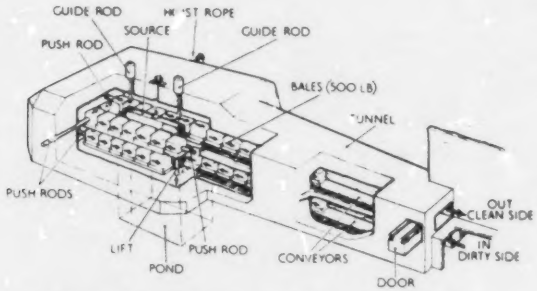

FIG. 46. Australian gamma irradiation plant for goat hair

12.2. Economics of irradiation

The elements of costs for irradiation are similar to those for any food manufacturing and distributing operation, namely (a) fixed costs associated with the facility, (b) variable costs associated with the operation of the facility and with the transportation of the food from point of production to point of consumption, including storage. Variable costs normally are charged off as they occur. Variable costs include items such as labour and supervision, utilities, supplies, maintenance and repair costs, taxes, etc. Fixed costs are usually prorated on some basis of time, which is related to the presumed useful life of the facility. The proration has to be somewhat arbitrary.

The useful features of an irradiation facility which affect cost are the radiation sources, the heavy shielding and the associated remote-operation equipment. This can account for one-half the plant cost. With adequate scale of operation and with a well-designed efficient facility, operating costs can be comparable with other conventional food processing operations.

The strength of the radiation source and, consequently, the cost, are related to the dose. The prorated fixed costs, therefore, are related to dose and since food applications can vary in dose from ca 10 krad to 5 Mrad, a factor of 500, the variation of these costs can be large. Therefore, at the high sterilizing doses, they can be the larger part of the costs.

The kind of radiation source employed can affect costs. There are at least two possible gamma sources (e.g. ^{60}Co, ^{137}Cs), both of which seem to have roughly equal overall costs. There is also the possibility of using X-ray machines, the economies of which are not fully available. It appears quite certain, however, that electron beams, which have a substantially higher conversion factor for line-power to ionizing radiation than X-ray

units, have a lower cost than X-rays. For large installations, it seems probable that the use of electron beams is the most economical form of ionizing radiation. However, the low penetrating power of electron beams has to be taken into consideration when deciding on which type of source to employ for food processing.

A comparison of total costs, both fixed and variable, suggests that high dose applications (e.g. sterilization) are likely to be larger than costs for thermal canning. Better texture and flavour of certain irradiated products may off-set added costs. Low dose costs tend to approximate those of other comparable food processes (e.g. freezing).

12.3. Commercial experience

There is limited commercial experience with irradiated foods. What has been obtained has occurred in only a few countries, and some of it has not been truly commercial, either because of the use as an experimental processing method or because of the manner in which the product has been distributed to the public.

The most experience has been obtained with potatoes. Marketing of this food has occurred in Canada and other countries. No unusual problems were encountered either with production, distribution, or public acceptance.

13. LITERATURE SOURCES

13.1. Publications of organizations

Much of the published work on food irradiation exists in the standard publications of food science and technology and related fields. Other reports of work have been issued by government and official groups, including the following:

(a) Food and Agriculture Organization of the United Nations,
Rome, Italy
(b) International Atomic Energy Agency,
Vienna, Austria
(c) Institute for Biology and Agriculture,
Reactor Centre Seibersdorf, Austria
(d) Atomic Energy of Canada, Limited,
Ottawa, Canada
(e) Israel Atomic Energy Commission,
Soreq Nuclear Research Centre,
Yavne, Israel
(f) Department of Scientific Research,
Cambridge, England
(g) United States of America
(1) US Dept of Agriculture,
Washington, D.C. 20025
(2) US Army Natick Laboratories,
Natick, Mass. 01760
(3) US Atomic Energy Commission,
Division of Technical Information,
Oak Ridge, Tenn. 37830

(4) US Dept of Commerce,
Washington, D.C. 20230
(5) US Dept of Health, Education, and Welfare,
Federal Food and Drug Administration,
Washington, D.C. 20204
(6) National Research Council, National Academy of Science,
Washington, D.C. 20418

In addition there have been publications by privately operated organizations such as:

(a) American Meat Institute Foundation,
Chicago, Ill., United States of America
(b) Danish Meat Research Institute,
Roskilde, Denmark

Two periodicals relating to food irradiation in whole or part are:

(a) Quarterly International Newsletter,
Food Irradiation,
European Information Centre for Food Irradiation,
Saclay, France
(b) International Atomic Energy Agency Bulletin,
Vienna, Austria

13.2. Books on food irradiation

The following is a list of some of the most useful books published on subjects relating specifically or partly to food irradiation.

AGLINTEV, K.K. (General Ed.), Applied Dosimetry, English translation of Russian (Moscow, 1962), London Iliffe Books, Ltd., London (1965).

AMERICAN CHEMICAL SOCIETY, Radiation Preservation of Foods (Proc. Symp. Atlantic City, N.J., 1965), American Chemical Society, Washington, D.C. (1967).

AMERICAN INSTITUTE OF CHEMICAL ENGINEERS, Chemical and Food Applications of Radiation, Symposium Series 83, 64, AICE, New York (1968).

ATOMIC ENERGY OF CANADA, LIMITED, The Radioisotope Handbook, AECL, Commercial Products, Ottawa, Canada (1966).

ATOMIC ENERGY OF CANADA, LIMITED, The AECL Radioisotope Applications Handbook, AECL, Commercial Products, Ottawa.

ATOMIC ENERGY OF CANADA, LIMITED, Gamma Irradiation in Canada 1-4, AECL, Commercial Products, Ottawa.

O'BRIEN, R.D., WOLFE, L.S., Radiation, Radioactivity and Insects. An American Institute of Biological Sciences and United States Atomic Energy Commission Monograph, Academic Press, New York (1964).

BROWNELL, L.E., Radiation Uses in Industry and Science, United States Atomic Energy Commission (1961), copies obtainable from Superintendent of Documents, US Government Printing Office, Washington, D.C.

CHARLESBY, A. (Ed.), Radiation Sources, Pergamon Press, Oxford (1964).

DESROSIER, N. W., ROSENSTOCK, H. M., Radiation Technology in Food, Agriculture and Biology, Avi Publishing Co., Westport, Conn. (1960).

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, The Technical Basis for Legislation on Irradiated Food (Rep. Joint FAO/IAEA/WHO Expert Committee, Rome, 1964), FAO, Rome (1966).

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Freezing and Irradiation of Fish, Fishing News, Ltd., London (1969).

HANNAN, R. S., Scientific and Technological Problems Involved in Using Ionizing Radiations for the Preservation of Foods, Department of Scientific and Industrial Research, Food Investigation, Special Report No. 61, Her Majesty's Stationery Office, London (1955).

INTERNATIONAL ATOMIC ENERGY AGENCY, Preservation of Fruit and Vegetables by Radiation, Panel Proceedings Series, IAEA, Vienna (1966).

INTERNATIONAL ATOMIC ENERGY AGENCY, Food Irradiation (Proc. Symp. Karlsruhe, 1966), IAEA, Vienna (1966).

INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation and Radioisotopes Applied to Insects of Agricultural Importance (Proc. Symp. Athens, 1963), IAEA, Vienna (1963).

INTERNATIONAL ATOMIC ENERGY AGENCY, Application of Food Irradiation in Developing Countries, Technical Reports Series No. 54, IAEA, Vienna (1966).

INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Control of Salmonellae in Food and Feed Products, Technical Reports Series No. 22, IAEA, Vienna (1963).

INTERNATIONAL ATOMIC ENERGY AGENCY, Microbiological Problems in Food Preservation by Irradiation (Rep. Panel organized by the Joint FAO/IAEA Division of Atomic Energy in Food and Agriculture, 1966), IAEA, Vienna (1967).

INTERNATIONAL ATOMIC ENERGY AGENCY, Enzymological Aspects of Food Irradiation (Proc. Panel organized by the Joint FAO/IAEA Division of Atomic Energy in Food and Agriculture, 1968), IAEA, Vienna (1969).

KUZIN, A. M., Radiation Biochemistry, English translation of Russian (Moscow, USSR, 1962), Israel Program for Scientific Translations, Jerusalem, Daniel Davey & Co., Inc., New York, N. Y. (1964).

LEA, D. E., Actions of Radiations on Living Cells, 2nd Edn (reprinted 1962), Cambridge University Press, UK.

MAXIE, E. C., ABDEL-KRAMER, A., "Food irradiation - physiology of fruits as related to feasibility of the technology", Advances in Food Research 15, Academic Press, Inc., New York, N. Y. (1966).

METLITSKII, L. V., ROGACHEV, V. I., KRUSHCHEV, V. G., Radiation Processing of Foods, Izdatel'stvo "Ekonomika" Moscow (1967), available as English translation (ORNL IIC-14) from Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, US Department of Commerce, Springfield, Va.

NATIONAL ACADEMY OF SCIENCES, Radiation Preservation of Foods (Proc. Int. Conf. Boston, Mass., 1964), Publication 1273, NAS, National Research Council, Washington, D.C. (1965).

NATIONAL COUNCIL ON RADIATION PROTECTION AND MEASUREMENTS, Radiation Protection in Educational Institutions, Washington, D.C. (1966).

PRICE, W.J., Nuclear Radiation Detection, 2nd Edn, McGraw-Hill Book Company, New York, N.Y. (1964).

PROCTOR, B.E., GOLDBLITH, S.A., "Electromagnetic radiation fundamentals and their applications in food technology", in Advances in Food Research 3, Academic Press, Inc., New York, N.Y. (1951).

ROMANI, R.J., "Radiological parameters in the irradiation of fruits and vegetables", Advances in Food Research 15, Academic Press, Inc., New York, N.Y. (1966).

SOMMER, N.F., FORTLAGE, R.J., "Ionizing radiation for control of postharvest diseases of fruits and vegetables", Advances in Food Research 15, Academic Press, Inc., New York, N.Y. (1966).

SPINKS, J.W.T., WOODS, R.J., An Introduction to Radiation Chemistry, John Wiley & Sons, Inc., New York (1964).

UNITED STATES ARMY QUARTERMASTER, Radiation Preservation of Food, US Army Quartermaster (1957), copies obtainable from US Department of Commerce, Office of Technical Services, Washington, D.C.

UNITED STATES ATOMIC ENERGY COMMISSION, Nuclear Terms, a brief glossary, USAEC, Division of Technical Information, Oak Ridge, Tenn.

UNITED STATES ATOMIC ENERGY COMMISSION, Food Preservation by Irradiation, USAEC, Division of Technical Information, Oak Ridge, Tenn.

UNITED STATES ATOMIC ENERGY COMMISSION, The Genetic Effects of Radiation, USAEC, Division of Technical Information, Oak Ridge, Tenn.

UNITED STATES ATOMIC ENERGY COMMISSION, Radiation Preservation of Foods (Proc. Symp. Kansas City, 1965, in connection with the Annual Meeting of the Inst. of Food Technologists), USAEC, Division of Technical Information Conf. 650552, available from Clearinghouse for Federal Scientific and Technical Information, National Bureau of Standards, US Department of Commerce, Springfield, Va.

UNITED STATES ATOMIC ENERGY COMMISSION, What's Available in the Atomic Literature?, USAEC, Division of Technical Information Extension, Oak Ridge, Tenn. (1966).

UNITED STATES ATOMIC ENERGY COMMISSION and INTERNATIONAL ATOMIC ENERGY AGENCY, Int. Conf. Preservation of Foods by Ionizing Radiations, Massachusetts Institute of Technology, Cambridge, Mass. (1959).

UNITED STATES DEPARTMENT OF COMMERCE, The Physical Aspects of Irradiation, Handbook 85, USDC, National Bureau of Standards, Washington, D.C. (1964).

UNITED STATES DEPARTMENT OF COMMERCE, Radioactivity, Recommendations of the International Commission on Radiological Units

and Measurements, Handbook 86, USDC, National Bureau of Standards, Washington, D. C. (1963).

UNITED STATES DEPARTMENT OF COMMERCE, Current Status and Commercial Prospects for Radiation Preservation of Foods, USDC, Business and Defense Services Administration, Washington, D. C. (1965).

UNITED STATES DEPARTMENT OF COMMERCE, Radiation Research (Proc. Int. Conf. Natick, Mass., 1963), USDC, Office of Technical Services, Washington, D. C. (1963).

UNITED STATES DEPARTMENT OF COMMERCE, The Commercial Prospects for Selected Irradiated Foods, copies obtainable from Superintendent of Documents, US Government Printing Office, Washington, D. C. (1968).

UNITED STATES DEPARTMENT OF COMMERCE, Food Irradiation Activities throughout the World, USDC, Business and Defense Services Admin., copies obtainable from Superintendent of Documents, US Government Printing Office, Washington, D. C. (1968).

UNITED STATES DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE, Radiological Health Handbook, Revised Edn, USDHEW, Public Health Service, Washington, D. C. (1960).

PART II

INTRODUCTION

LABORATORY EXERCISES

INTRODUCTION

One of the best ways to become familiar with new techniques, is to observe, or actively participate in well organized laboratory demonstrations of the use of the technique. This is particularly true with the use of ionizing radiation as a food processing method. The action of the radiation on the food is quite different from that of heat processing or other conventional methods. The colour, texture and flavour may be different, as the objective accomplished may be different from that gained by other commonly used processes. Therefore, it is believed to be highly desirable that certain types of demonstrations be carried out, so that the trainee may observe the manner in which the treatment is carried out and the effects that are produced in the food product.

In some cases it may not be possible to allow the trainee to carry out the experiments independently of the instructor. For example, experiments involving microorganisms requiring very special techniques and the maintaining of aseptic conditions is important and cannot be taught to students during a single experiment. Therefore, only those with some training in microbiology could successfully carry out meaningful experiments on their own.

There follows a number of suggested exercises that can be used to demonstrate the use of ionizing radiation to accomplish specific objectives in the treatment of food products for their preservation.

The exercises described below are intended to provide the trainees with laboratory exercises in the following important aspects of food irradiation: (1) dosimetry; (2) radiation chemistry; (3) radiation microbiology; (4) preservation of foods; (5) sensory evaluation of foods and (6) control of insect infestation.

The time allotted for demonstration exercises may not be sufficient to permit all of the suggested exercises to be used, and therefore, a selection should be made of those in the fields of greatest interest and value to the trainees involved.

LABORATORY EXERCISES

LABORATORY EXERCISE 1

1. IRRADIATION DOSIMETRY BY THE FRICKE METHOD

In 1963, the American Society for Testing and Materials adopted a "Standard Method of Test for Absorbed Gamma Radiation Dose in the Fricke Dosimeter". (ASTM Standards, Part 29 (1967) 735.) This laboratory exercise demonstrates the use of this method for measuring absorbed radiation in the range of 0.2×10^4 to 4×10^4 rad. In this range, the oxidation of ferrous ammonium sulphate with the production of ferric ions are linearly related to dose. The method is independent of (a) dose rate up to 10^7 rad per hour, (b) temperature between 0 and 50°C, and (c) radiation energy in the range of 0.1 to 2 MeV.

1.1. Preparation and standardization of the ferric solution

All glassware must be cleaned in dichromate-H_2SO_4 cleaning solution, thoroughly rinsed with distilled water and finally rinsed with triple distilled water.

All reagents and solutions must be made up with triple distilled water. All chemicals must be of the highest purity.

(1) Prepare a 0.4 M solution by using 20.0 g of ferric sulphate made up to 1 litre with 0.4 M H_2SO_4. Place this solution (in bottle with loose cap) in an oven at 90 to 95°C overnight to dissolve. This solution will be standardized and used for the standard curve: optical density (OD_{305}) versus ferric ions (or dose in rads).

(2) Dry a quantity of $K_2Cr_2O_7$ by heating at 110-126°C for 3 hours. Make up a solution of dichromate (0.1 N) containing exactly 4.904 g per litre (triple distilled water). This weighing is critical and must be carried out rapidly in dry conditions. The solution should stand a few hours at ambient temperature before use.

(3) Make up a solution of 60 g of stannous chloride in 600 ml of concentrated HCl. Make up to 1 litre.

(4) Prepare a mixture of 150 ml of concentrated H_2SO_4 and 150 ml of concentrated H_3PO_4 made up to 1 litre.

(5) Prepare a saturated solution of $HgCl_2$ (60 - 70 g/litre).

(6) Make up a 0.2% solution of diphenylamine or diphenylamine sulphonate (indicator).

(7) Place 20 ml of the ferric solution in a clean flask and heat gently to almost boiling point. Add approximately 4.5 ml of the stannous chloride solution and mix until all ferric ions are reduced to ferrous. (Yellow colour changes to colourless.)

(8) Cool the mixture to ice/water bath temperature and add 15 ml of ice cold H_2SO_4-H_3PO_4 solution. Mix and then add 5 ml of

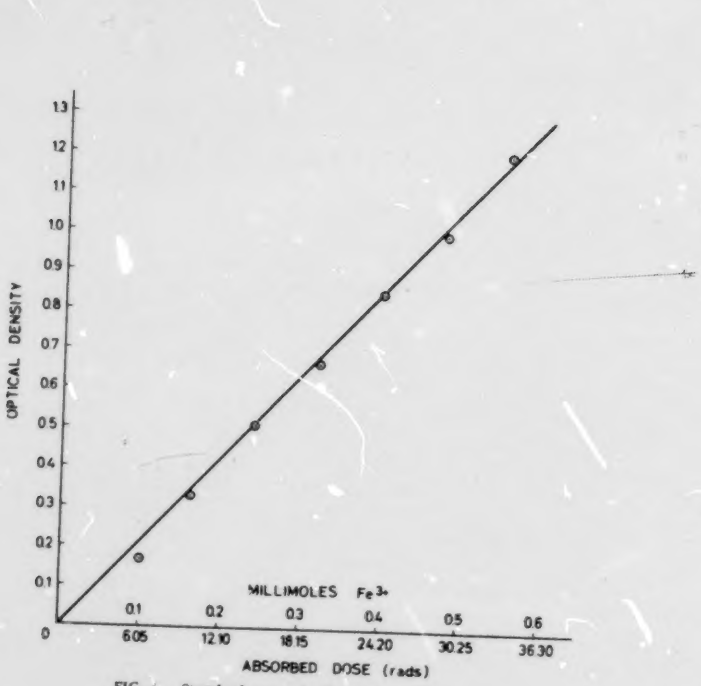

FIG. A. Standard curve for Fricke dosimetry

the $HgCl_2$ solution (also ice cold). Add 3 to 4 drops of the indicator solution. A fine, silky, light coloured precipitate will normally appear. Darkening of this precipitate indicates an undesirable reduction of $HgCl_2$ to metallic mercury, probably caused by an excess of $SnCl_2$ and also by failing to cool the solutions adequately.

(9) From a burette now run in about 19 ml of the 0.1 N dichromate solution slowly, then dropwise until the endpoint is reached. The green colour changes to violet.

(10) From the amount of dichromate used calculate the molarity of the ferric ion solution. (Note: 1 molar $Fe_2(SO_4)_3$ would be 2 normal, but 1 molar in "ferric ion" would be 1 normal.)

$$\text{Molarity } Fe^{3+} = \text{normality } Fe^{3+} = \frac{(0.1)\ (\text{cm}^3 \text{ dichromate used})}{(20)}$$

1.2. Procedure

1.2.1. Standard curves

(1) Dilute the ferric solution (0.1 M) with 0.4 M H_2SO_4 to obtain about 0.0001, 0.0002, 0.0003, 0.0004, 0.0005, 0.0006 and 0.007 M solution of ferric ion.

(2) Read the optical density (absorbance) of the diluted solutions in the Beckman spectrophotometer set at 305 nm and slit width of 0.5 mm (must use matched cells if more than one quartz cell is to be used; 0.4 M H_2SO_4 is used as the blank).

(3) Draw a standard curve plotting optical density versus concentration of ferric ion.
(4) Convert micromoles per litre of Fe^{3+} to rad by equation rad = micromoles Fe^{3+} per litre × 60.5.
(5) Draw a standard curve plotting optical density versus rad, such as Fig.A.

1.2.2. Dosimetry of a radiation source

(1) Prepare a solution that is 0.001 M in ferrous ammonium sulphate, 0.001 M in sodium chloride and 0.4 M in sulphuric acid using triple distilled water.
(2) A convenient way is to make up a stock solution 0.5 M in Fe^{2+} and 0.5 M in sodium chloride (196.07 g ferrous ammonium sulphate, 29.225 g NaCl made up to 1-litre with 0.4 M H_2SO_4). This stock solution may be stored for up to 3 months. On the day when a test is to be run dilute 2 ml of the stock solution to 1 litre with 0.4 M H_2SO_4 solution freshly saturated with oxygen.
(3) Place measured quantities in clean[1] glass vials, seal and place vials in different parts of source and irradiate. Time of residence in the source must be measured with stop watch. Position of a particular vial in the source must be known and recorded.
(4) Remove vials from source and determine optical density of solution, using unirradiated solution as a blank (optical density of blank must be less than 0.4)[2].

1.3. Results

(1) Determine the total absorbed radiation dose for each vial from the standard curve, Fig.A.
(2) Determine the dose rate for the source.

---

[1] Clean glass vials can be filled with dosimetric solution, exposed to a dose of about 30 krad, emptied and reused immediately (without further rinsing) for the actual dosimetric procedure. Theory: that any contaminating material which would affect the ferrous/ferric system will react and be removed.

[2] Optical density measurements should be made at a constant temperature, otherwise, correct for temperature.

$$\text{Correction} = \frac{\text{dose measured at } T_2}{1 + 0.007(T_2 - T_1)}, \text{ where}$$

T_1 = temperature at which calibration curve was prepared (degC), and
T_2 = temperature at which irradiated sample is read (degC).

LABORATORY EXERCISE 2

2. RADIATION CHEMISTRY – Determination of effects of radiation on ascorbic acid (vitamin C) in food

2.1. Purpose

To demonstrate the effect of ionizing radiation on vitamin C, with respect to the nature of the substrate, in which the compound is contained, the total dose absorbed and the direct and indirect actions involved (see section 4.3 5. of Part I).

2.2. Materials

(1) Fresh orange juice
(2) Glacial HPO_3 pellets
(3) Glacial acetic acid
(4) Crystalline ascorbic acid (VSP reference ascorbic acid). Keep cool, dry and cut off direct sunlight
(5) 2,6 dichloroindophenol sodium salt
(6) Soda lime
(7) $NaHCO_3$
(8) Filter paper, plain and fluted
(9) Amber glass stoppered bottles, 500 ml
(10) 3 Erlenmeyer flasks, 50 ml
(11) Burette, 50 ml
(12) Volumetric flasks and pipettes
(13) Desiccator
(14) Distilled water

2.3. Procedure

This is the method for ascorbic acid of the Association of Official Agricultural Chemists and is applicable to food products provided that they do not contain ferrous, stannous or cuprous ions, SO_2 or thiosulphate.

2.3.1. Preparation of reagents

(1) Metaphosphoric acid – acetic acid stabilizing extracting solution. Dissolve, with shaking, 15 g of glacial HPO_3 pellets, or freshly pulverized stick HPO_3, in 40 ml of acetic acid and 200 ml distilled water. Dilute to 500 ml and filter rapidly through fluted filter paper into a glass stoppered bottle. (HPO_3 slowly changes to H_3PO_4, but if stored in refrigerator will remain satisfactory for 7 to 10 days.)
(2) Indophenol standard solution. Dissolve 50 mg of 2,6 dichloroindophenol sodium salt, that has been stored in a desiccator over soda lime, in 50 ml of distilled water to which has been added 42 mg of $NaHCO_3$. Shake vigorously, and when the dye is dissolved, dilute to 200 ml. Filter through fluted filter paper into an amber glass stoppered bottle. Keep the bottle stoppered, and out of direct light, in a refrigerator.

TABLE A. DATA SHEET FOR ASCORBIC ACID IRRADIATION

	(1) Orange juice		(2) Distilled water ascorbic acid solution		(3) Distilled water solution of irradiated dry ascorbic acid crystals	
Dose (krad)	mg ascorbic acid per 100 ml	percentage destruction	mg ascorbic acid per 100 ml	percentage destruction	mg ascorbic acid per 100 ml	percentage destruction

Note (check this solution by adding 5.0 ml of the extracting solution, (1) above, containing ascorbic acid, to 15 ml of the indophenol dye reagent. If the reduced solution is not practically colourless, discard and prepare a fresh stock solution. If the dry dye is at fault, use a new batch.)

(3) Reference standard ascorbic acid solution.
Weigh accurately (± 0.1 mg) about 100 mg of crystalline ascorbic acid, transfer to a 100 ml glass stoppered volumetric flask and dilute to volume with HPO_3-HOAc reagent at room temperature.

(4) Standardize the indophenol solution at once as follows:
Transfer three 2.0 ml aliquote of the ascorbic acid solution to each of three 50 ml Erlenmeyer flasks containing 5.0 ml of the HPO_3-HOAc reagent. Titrate rapidly with the indophenol solution from the 50 ml burette until a light but distinct rose-pink colour persists for at least 5 seconds. (Each titration should require about 15 ml of solution.) Titration should check within 0.1 ml.

Similarly titrate three blanks composed of 7.0 ml of the HPO_3-HOAc reagent plus a volume of the H_2O equivalent to the volume of indophenol solution used in the direct titration.

After subtracting the average of the blanks (usually about 0.1 ml) from the standardization titrations, calculate and express the concentration of indophenol solution as mg ascorbic acid equivalent to 1.0 ml of reagent. The indophenol solution should be standardized daily with a freshly prepared solution of reference standard ascorbic acid solution.

2.3.2. Determination of ascorbic acid in the orange juice

(1) Express juice from a number of oranges to yield at least one litre of juice. Mix thoroughly and set aside one half the juice in an amber bottle in the refrigerator for irradiation. Filter the other half through absorbant cotton or rapid paper filter, and analyse as follows:

(2) Add aliquote of at least 100 ml of the orange juice to an equal volume of the HPO_3-HOAc reagent. Mix and filter rapidly through rapid folded paper. (Eaton-Dikeman No.195, 18.5 cm, or equivalent.) Titrate 10 ml aliquote with the standardized indophenol solution and make blank determinations for correction of the titrations, as described above, using appropriate volumes of HPO_3-HOAc reagent and H_2O. Express ascorbic acid concentration as mg/100 ml of original sample.

2.3.3. Determination of ascorbic acid in a known solution

(1) Weigh out an amount of crystalline ascorbic acid in 500 ml of distilled water, to approximate the ascorbic acid content found in the orange juice above (section 2.3.2.).

(2) Add 100 ml aliquote of the known ascorbic acid solution to 100 ml of the HPO_3-HOAc reagent. Titrate 10 ml aliquote with the standardized indophenol solution, and make blank determinations, and express the results as mg/100 ml of ascorbic acid.

2.3.4. Demonstration of the effect of radiation on ascorbic acid

(1) Dispense 3 aliquots of 100 ml of the original orange juice, that was set aside for irradiation, and 4 aliquots of 100 ml of the distilled water solution of ascorbic acid, into thoroughly cleaned glass containers suitable for irradiation (e.g. 25 × 200 mm borosilicate glass culture tubes). Place some ascorbic acid crystals in 3 dry tubes such as used for the liquids. Each tube should contain the same weighed amount of crystalline ascorbic acid, to make a 500 ml solution of approximately the same ascorbic acid concentration as the orange juice and the water solution.
(2) Set aside one of the tubes of the water solution of ascorbic acid to act as a non-irradiated control.
(3) Irradiate one of the tubes of each of the three lots (juice, water solution and dry crystals) at each of the radiation doses of 10, 100 and 1000 krad.
(4) After the irradiation treatment carefully transfer the weighed amount of crystalline ascorbic acid to 500 ml volumetric flasks and fill to volume with distilled water.
(5) Add the 100 ml of each of the 9 irradiated samples to 100 ml of the HPO_3-HOAc reagent. Titrate 10 ml aliquots of each with the standardized indophenol solution and calculate the ascorbic acid content of each sample.
(6) Make the same titration with the sample of the water solution of ascorbic acid, that was set aside as the non-irradiated control. Record results in Data Sheet, Table A.

2.4. Results

2.4.1. Evaluation of the effect of radiation on ascorbic acid under different conditions

(1) From the results obtained by the various titrations of ascorbic acid in the different solutions:

   (a) Compare the effect of the radiation dose in each of the types of solutions of ascorbic acid.
   (b) Compare the effect of radiation at the same dose for each of the different types of solutions of ascorbic acid.

(2) It should be found that the loss of ascorbic acid in each type of solution is roughly proportioned to the absorbed radiation dose. Plot ascorbic acid concentration against absorbed dose.
(3) The effect of a given dose on the three different lots of ascorbic acid should be in the following order of increasing destruction:
   dry crystals < whole orange juice < distilled water solution.
This illustrates the direct effect in the crystals and the indirect effect due to free radicals, in the solutions.

3. EFFECT OF RADIATION ON THE GERMINATION OF SEEDS[3]

3.1. Purpose

The purpose of this exercise is to demonstrate the effect of gamma radiation on germination of seeds and also the effect on the sprouts that do germinate.

3.2. Materials

(1) Green bean seeds
(2) Corn seeds
(3) Vermiculite (expanded mica)

3.3. Procedure

(1) Place 30 seeds of either corn or green beans in 8 small plastic bags and irradiate with 0, 0.5, 1, 5, 10, 20, 50 and 100 krad.
(2) Plant the seeds in trays containing vermiculite at a depth of about 2 inches (4.5 cm). Moisten the vermiculite and place the trays in a space controlled at about 30°C.

3.4. Results

(1) Examine daily and record the number (or percentage) of sprouted seeds for each dose.
(2) Note the characteristics of the seedlings that grow. Measure the approximate lengths of the sprouts in each case.
(3) Plot the dose against length of sprouts.

[3] This study should be carried out under conditions that the seedlings are exposed to at least 12 hours of daylight each day.

LABORATORY EXERCISE 4

4. EFFECT OF GAMMA RADIATION ON INACTIVATION OF INSECTS

4.1. Purpose

The purpose of this laboratory experiment is to determine the resistance of some insects (adult stage) to radiation.

4.2. Procedure

(1) Place 25 adult flour beetles (Tribolium confusum) into each of 5 Petri plates (100 mm diameter).
(2) Place 10 adult male cockroaches (Periplaneta americana) into each of 10 large Petri dishes (200 mm diameter).
(3) Irradiate 25 flour beetles and 20 cockroaches with 0, 10, 25, 50 and 100 krad.
(4) After irradiation, place a small amount of flour in each Petri dish containing flour beetles. In the Petri dishes containing the cockroaches, place a pellet of compressed dried animal food and a vial of water with a cotton wick.
(5) Store the insects at 30°C.

4.3. Results

(1) Each day note the number of dead insects and for each dose treatment plot the per cent survival as a function of the number of days elapsed following irradiation.
(2) Plot the time (days) for 50% survival as a function of radiation dose.

LABORATORY EXERCISES 5.1.TO 5.4.

5.1. RADIATION MICROBIOLOGY - Determining the D_{10} radiation dose of microorganisms
(see section 5.2.2. of Part I).

5.1.1. Purpose

To demonstrate the method of determining the sensitivity of microorganisms to radiation and to establish the dose necessary to reduce the population by a factor of 10, or one log cycle.

5.1.2. Materials

(1) Bacterial culture of a suitable vegetative organism, such as Pseudomonas fluorescens.
(2) Peptone dilution fluid (0.1% peptone, 0.85% sodium chloride, pH 7.0).
(3) Test tubes
(4) Petri plates
(5) Total plate count agar (standard method agar)
(6) Incubator, set at 30°C
(7) Water bath set at 45°C

5.1.3. Procedure

(1) The instructor will prepare a suitable culture of the test organism in advance. This should have a population of 10^5 - 10^8 per ml.
(2) The organisms should be suspended in peptone dilution water and from this the same amount placed in tubes appropriate for radiation treatment. The suspensions should be made in duplicate for each radiation dose selected, and for the control.
(3) The radiation doses selected will depend on the particular organism being tested, and the previous experience of the instructor in determining the D_{10} value under the condition existing. These factors are important to the success of the experiment. It is suggested that the radiation doses selected fall in the range of 1000 rad to 20 krad.
(4) Perform the radiation very carefully, using a stop watch to determine the dwell time of the tubes in the radiation field. Calculate the dose received by the organisms based upon dosimetry readings made just before running the experiment.

5.1.4. Results

(1) Immediately after the radiation make a series of dilutions in peptone water from all tubes in the experiment, including the control. These dilutions should span the expected populations of the experiment so as to give countable plates, with between 30 and 300 colonies per plate.

(2) Place aliquots of these dilutions, in duplicate, into Petri plates and pour at once with the total plate count agar. The agar must have been held in the 45°C water bath to ensure a uniform temperature, so that all organisms will receive the same heat shock at the time of pouring of the plates.
(3) When the agar has solidified invert the plates and place in the 30°C incubator. This temperature is selected because the Pseudomonas group of organisms are cold tolerant and grow better at less than body temperature. Incubate for 3 days.
(4) Count all plates having between 30 and 300 colonies. Average the counts of the duplicate plates.
(5) Plot the log of the surviving organisms against the radiation dose received (see Fig.17).
(6) From the curves constructed from the results of the experiment determine the D_{10} value by reading the number of rads necessary to reduce the initial population by one log cycle.

$$D_{10} = \frac{\text{dose in rads}}{\log a - \log b}$$

where a = the initial number of bacteria (the count of the control) and b = the number of bacteria surviving the radiation dose. If one plots the $\log_{10}$ of the number of survivors versus the dose (semilog plot) one gets a straight line in the exponential portion of the "survivor curve". D_{10} is the reciprocal of the slope of the straight line portion, or the dose for the curve to traverse one logarithmic cycle (the 90% destruction or 10% survival dose).

5.2. RADIATION MICROBIOLOGY – Radiation resistance of Salmonella[4]

5.2.1. Purpose

The purpose of this exercise is to determine the radiation resistance of a non-sporeforming bacterium and also to become acquainted with the quantitation of an important pathogenic enterobacteriaceae, Salmonella typhimurium, by the most probable numbers (MPN) method.

5.2.2. Materials

(1) Trypticase soy broth (BBL)[5] to which has been added 5 g yeast extract per litre
(2) Tryptic soy agar (Difco)[6] to which has been added 5 g yeast extract per litre
(3) Selenite-cystine broth (Difco)
(4) M/75 phosphate buffer pH 7
(5) Brilliant green agar (Difco)

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[4] UNITED STATES PUBLIC SERVICE, Examination of Foods for Enteropathogenic and Indicator Bacteria, US Public Service Publication Nr.1142.

[5] Baltimore Biological Laboratories, Baltimore, Md.

[6] Difco Laboratories Inc., Detroit, Mich.

(6) Polyvalent Salmonella 0 antiserum (Difco)
(7) Malonate broth
(8) Simmons' citrate broth

5.2.3. Procedure

(1) Inoculate 10 ml trypticase soy yeast extract (TSYE) broth with a pure culture of Salmonella typhimurium and incubate for about 15 hours at 37°C. The cell concentration should be about 10^8 to 10^9 per ml. Add 1 ml to 50 ml sterile TSYE broth.
(2) Place 8 ml portions into 6 empty sterile culture tubes.
(3) Irradiate with the following doses and then make decimal dilutions (1-10) of the irradiated cultures using chilled phosphate buffer, pH 7.

Dose	Dilution to make
0	10^{-7}, 10^{-8}, 10^{-9}, 10^{-10}
20 krad	10^{-6}, 10^{-7}, 10^{-8}, 10^{-9}
50 krad	10^{-4}, 10^{-5}, 10^{-6}, 10^{-7}
80 krad	10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}
110 krad	10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}
140 krad	10^{0}, 10^{-1}, 10^{-2}, 10^{-3}

(4) Pipette 1 ml of each dilution into each of 5 tubes of sterile selenite cystine broth
(5) Incubate the tubes at 37°C for 48 hours
(6) If the broth remains clear after 48 hours, it means no Salmonella was present. However, if the broth turns red or becomes turbid, microbial growth is indicated and we must test if this is due to Salmonella by streaking a loopful of the broth from each tube on the surface of prepoured brilliant green agar plates. The plates are incubated for 24 - 48 hours at 37°C, and the presence of pink or translucent colonies surrounded by a red zone is presumptive evidence of Salmonella. A confirmatory test for Salmonella is then made by subjecting these colonies to the following tests:

(7) Test	Typical Salmonella reaction
(a) Gram stain	gram negative rods
(b) Inoculation into triple sugar iron agar	alkaline slant (red) and acid butt (yellow) usually with blackening due to H_2S production
(c) Inoculation into lysine iron agar	presence of lysine decarboxylase causes an alkaline (purple) reaction. Iron sulphide also formed
(d) Inoculation into malonate broth	no growth in this medium
(e) Inoculation into Simmon's citrate broth	growth (utilizes citrate as a carbon source)
(f) Agglutination reaction with polyvalent Salmonella 0 antiserum and Salmonella H antiserum	cells clump together

TABLE B. MOST PROBABLE NUMBERS - COLIFORM GROUP TESTS

Most probable numbers per 100 ml of sample, planting 5 portions in each of 3 dilutions in geometric series

(1)			(2)	(1)			(2)	(1)			(2)	(1)			(2)	(1)			(2)	(1)			(2)
10	1	0.1		10	1	0.1		10	1	0.1		10	1	0.1		10	1	0.1		10	1	0.1	
0	0	0		1	0	0	2	2	0	0	4.5	3	0	0	7.8	4	0	0	13	5	0	0	23
0	0	1	1.8	1	0	1	4	2	0	1	6.8	3	0	1	11	4	0	1	17	5	0	1	31
0	0	2	3.6	1	0	2	6	2	0	2	9.1	3	0	2	13	4	0	2	21	5	0	2	43
0	0	3	5.4	1	0	3	8	2	0	3	12	3	0	3	16	4	0	3	25	5	0	3	58
0	0	4	7.2	1	0	4	10	2	0	4	14	3	0	4	20	4	0	4	30	5	0	4	76
0	0	5	9	1	0	5	12	2	0	5	16	3	0	5	23	4	0	5	36	5	0	5	95
0	1	0	1.8	1	1	0	4	2	1	0	6.8	3	1	0	11	4	1	0	17	5	1	0	33
0	1	1	3.6	1	1	1	6.1	2	1	1	9.2	3	1	1	14	4	1	1	21	5	1	1	46
0	1	2	5.5	1	1	2	8.1	2	1	2	12	3	1	2	17	4	1	2	26	5	1	2	64
0	1	3	7.3	1	1	3	10	2	1	3	14	3	1	3	20	4	1	3	31	5	1	3	84
0	1	4	9.1	1	1	4	12	2	1	4	17	3	1	4	23	4	1	4	36	5	1	4	110
0	1	5	11	1	1	5	14	2	1	5	19	3	1	5	27	4	1	5	42	5	1	5	130
0	2	0	3.7	1	2	0	6.1	2	2	0	9.3	3	2	0	14	4	2	0	22	5	2	0	49
0	2	1	5.5	1	2	1	8.2	2	2	1	12	3	2	1	17	4	2	1	26	5	2	1	70
0	2	2	7.4	1	2	2	10	2	2	2	14	3	2	2	20	4	2	2	32	5	2	2	95
0	2	3	9.2	1	2	3	12	2	2	3	17	3	2	3	24	4	2	3	38	5	2	3	120
0	2	4	11	1	2	4	15	2	2	4	19	3	2	4	27	4	2	4	44	5	2	4	150
0	2	5	13	1	2	5	17	2	2	5	22	3	2	5	31	4	2	5	50	5	2	5	180
0	3	0	5.6	1	3	0	8.3	2	3	0	12	3	3	0	17	4	3	0	27	5	3	0	79
0	3	1	7.4	1	3	1	10	2	3	1	14	3	3	1	21	4	3	1	33	5	3	1	110
0	3	2	9.3	1	3	2	13	2	3	2	17	3	3	2	24	4	3	2	39	5	3	2	140
0	3	3	11	1	3	3	15	2	3	3	20	3	3	3	28	4	3	3	45	5	3	3	180
0	3	4	13	1	3	4	17	2	3	4	22	3	3	4	31	4	3	4	52	5	3	4	210
0	3	5	15	1	3	5	19	2	3	5	25	3	3	5	35	4	3	5	59	5	3	5	250
0	4	0	7.5	1	4	0	11	2	4	0	15	3	4	0	21	4	4	0	34	5	4	0	130
0	4	1	9.4	1	4	1	13	2	4	1	17	3	4	1	24	4	4	1	40	5	4	1	170
0	4	2	11	1	4	2	15	2	4	2	20	3	4	2	28	4	4	2	47	5	4	2	220
0	4	3	13	1	4	3	17	2	4	3	23	3	4	3	32	4	4	3	54	5	4	3	280
0	4	4	15	1	4	4	19	2	4	4	25	3	4	4	36	4	4	4	62	5	4	4	350
0	4	5	17	1	4	5	22	2	4	5	28	3	4	5	40	4	4	5	69	5	4	5	430
0	5	0	9.4	1	5	0	13	2	5	0	17	3	5	0	25	4	5	0	41	5	5	0	240
0	5	1	11	1	5	1	15	2	5	1	20	3	5	1	29	4	5	1	48	5	5	1	350
0	5	2	13	1	5	2	17	2	5	2	23	3	5	2	32	4	5	2	56	5	5	2	540
0	5	3	15	1	5	3	19	2	5	3	26	3	5	3	37	4	5	3	64	5	5	3	920
0	5	4	17	1	5	4	22	2	5	4	29	3	5	4	41	4	5	4	72	5	5	4	1600
0	5	5	19	1	5	5	24	2	5	5	32	3	5	5	45	4	5	5	81	-	-	-	-

(1) Number of positive tubes in each of these three dilutions (2) MPN per 100 ml

5.2.4. Results

(1) When it has been determined which selenite cystine tubes were really positive for Salmonella, then for each dilution, tabulate the number of tubes out of five that were positive.

As an example, let us consider that for the control sample, five out of five tubes (5/5) were positive for the 10^{-7} dilution, three out of five tubes (3/5) were positive for the 10^{-8} dilution, one out of five tubes (1/5) was positive for the 10^{-9} dilution, and none out of five tubes (0/5) was positive for the 10^{-10} dilution. Starting with the nighest dilution in which all five tubes were positive, record this number, 5, and also the number of positive tubes for the next two successive dilutions. For our example this would be 531.

Referring to the statistical table, Table B, of most probable numbers, and for the value 531 we determine the most probable numbers of Salmonella per 100 ml. However, the numbers cited in these tables are for the particular case where the initial inoculum was 10 ml. However, in any given test, the inoculum at which 5/5 positive tubes are obtained may be much smaller than 10 ml. In our example 5/5 positive tubes were obtained for an inoculum size of 10^{-7} ml. Therefore, the most probable numbers obtained from the table must be multiplied by the appropriate dilution factor. The difference between 10^{1} and 10^{-7} is 10^{8}, and gives the count per 100 ml.

5.3. RADIATION MICROBIOLOGY - Effect of radiation on bacterial spores

Determination of the radio resistance of spores of Clostridium sporogenes P.A. 3679.

5.3.1. Purpose

The purpose of this laboratory exercise is to demonstrate the radiation resistance of bacterial spores and also to demonstrate the technique for the quantitation of anaerobic bacteria.

5.3.2. Materials

(1) Wynne's medium:[7]

Yeast extract	10 g
BBL thioglycollate supplement	5 g
soluble starch	1 g
K_2HPO_4	2 g
distilled water	1 litre
adjust pH to 7.4 with NaOH solution agar	15 g

sterilize 15 minutes at 15 pounds steam pressure.

[7] WYNNE, E.S., SCHEIDING, W.R., DAYE, G.T., A simplified medium for counting Clostridium spores, Food Research, J. Food Sci. 20 (1955) 9-12.

(2) 5% $NaHCO_3$ solution.
Sterilize by Seitz filtration or passage through a membrane filter (millipore).
(3) Overlay agar:
1.5% agar solution containing 0.5% sodium thioglycollate.
Sterilize 15 minutes at 15 pounds steam pressure.
(4) Phosphate buffer solution.

5.3.3. Procedure

(1) A broth spore suspension of Clostridium sporogenes P.A. 3679 will be provided, at the spore concentration of approximately 1×10^7 per ml.
(2) Heat shock this spore suspension for 5 minutes at 100°C, cool and then place 10 ml portions into 5 sterile culture tubes taking care to avoid aeration.
(3) Irradiate the tubes in an ice water bath (0°C) or at 0°C in air, with the following doses and then make the following dilutions of the irradiated samples using M/75 phosphate buffer pH 7.

Dose	Dilution to make
0	10^{-5}, 10^{-6}
200 krad	10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}
400 krad	10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}
600 krad	10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}
800 krad	10^{0}, 10^{-1}, 10^{-2}, 10^{-3}
1000 krad	10^{0}, 10^{-1}, 10^{-2}

(4) Place 1 ml of each dilution into each of two flat oval tubes (Miller-Prickett tubes) containing 0.3 ml of the bicarbonate solution per tube. Add approximately 10 to 12 ml of melted Wynne's agar (50°C) to each tube and allow to solidify. Stratify each tube with about 3 ml of the overlay agar.
(5) Incubate the tubes for 24 to 48 hours at 37°C. Count the total number of colonies in those tubes which contain 5 to 50 colonies. Multiply by the dilution factor to obtain the concentration of spores per ml of the undiluted sample.

5.3.4. Results

(1) Construct the survival curve by plotting the log number of viable spores (ordinate) as a function of dose (abscissa).
(2) Determine the decimal reduction dose (D_{10} dose) as the number of rads required to reduce the spore concentration by a factor of 10.

5.4. RADIATION MICROBIOLOGY - Enumeration of microorganisms in an irradiated food

Determination of the number of viable microorganisms (total plate count) in irradiated (150 krad) and non-irradiated codfish fillets held for 1 week at 38°F (3.3°C).

5.4.1. Purpose

The purpose of this laboratory exercise is to demonstrate the technique of determining the viable bacterial concentration of a food, and also to demonstrate the reduction in bacterial concentration caused by a radiation-pasteurizing dose of gamma radiation.

5.4.2. Materials

(1) Sterile blendors, forceps, scissors
(2) Pre-poured plates of tryptic soy-yeast extract agar (TSYEA) which have been kept 1 to 2 days at room temperature to permit drying
(3) Sterile bent glass rods
(4) Sterile M/75 phosphate buffer pH 7 – Na_2HPO_4 – 5.68 g
KH_2PO_4 – 3.63 g
6 litres of distilled water

5.4.3. Procedure

(1) Weigh aseptically 30 g of fish into a sterile blendor. Add 270 ml of chilled sterile phosphate buffer diluent. Blend for 3 minutes. This is the 10^{-1} dilution.
(2) Make the following dilutions using chilled phosphate buffer

Dose	Dilution to make
control (air-pack)	10^{-3}, 10^{-4}, 10^{-5}
control (vacuum pack)	10^{-3}, 10^{-4}, 10^{-5}
150 krad (air-pack)	10^{-1}, 10^{-2}, 10^{-3}
150 krad (vacuum pack)	10^{-1}, 10^{-2}, 10^{-3}

(3) Pipette 0.1 ml of each dilution in duplicate on the surface of TSYE agar plates and spread this uniformly over the surface using a sterile bent glass rod.
(4) Incubate the plates at 20°C for 5 days.

5.4.4. Results

Count those plates which contain 30 to 300 colonies and multiply the count by the appropriate dilution factor to get the total plate count per gram of fish.

LABORATORY EXERCISE 6

6. INHIBITION OF MATURATION – Sprout inhibition of potatoes and onions

6.1. Purpose

The purpose of this exercise is to demonstrate that a low dose of radiation can inhibit sprouting of certain tuberous and bulbous vegetables, and that the dose may be different according to species.

TABLE C. SPROUT INHIBITION OF POTATOES

Storage time	Total number of sprouts				Per cent sprouted samples			
	control	5 krad	10 krad	20 krad	control	5 krad	10 krad	20 krad

TABLE D. SPROUT INHIBITION OF ONIONS

Storage	Per cent sprouted samples			
	Control	5 krad	10 krad	20 krad

6.2. Materials

(1) Select potatoes and onions that have not been chemically or radiation treated for sprout inhibition
(2) 8 perforated polyethylene bags that will hold 6 of the potatoes or onions
(3) Place potatoes or onions in bags and seal the top

6.3. Procedure

(1) Irradiate the bags at 0, 5, 10 and 20 krad.
(2) Immediately after irradiation place samples in an incubator at 30°C.

6.4. Results

(1) Periodically examine all samples for sprouting, noting the total number of sprouts in each lot.
(2) Determine the total number of sprouts in each lot and the per cent of sprouted samples and record in copies of the attached Tables C and D.
(3) At the termination of the storage test cut each potato or onion in half, length-wise, and examine for internal evidence of sprouting or rotting.

LABORATORY EXERCISES 7.1. AND 7.2.

7.1. EXTENSION OF MARKET LIFE OF A FOOD BY IRRADIATION - Evaluation of extension of market life by radiation treatment of fresh fish

7.1.1. Purpose

This exercise is intended to illustrate the effect of radiation treatment on the extension of the market life of a food normally held at refrigeration temperatures, and the changes in microbial flora that bring about food deterioration.

7.1.2. Materials

(1) 40 fillets (or steaks) of non-fatty fish, not to exceed 500 g each
(2) 20 clear plastic film wraps or bags
20 clear plastic film bags, suitable for vacuum packing
(3) Refrigerator, set at 3°C
(4) 120 sterile Petri plates for bacterial counts
(5) 120 sterile saline dilution blanks (99 ml after sterilization)
(6) 120 sterile 1 ml pipettes
(7) Sterile, total plate count agar (standard methods)
(8) Incubator, set at 30°C

7.1.3. Procedure

(1) Package 20 fillets in plastic bags or wraps (air-pack).
(2) Package 20 fillets in plastic bags and seal under vacuum.
(3) Place 5 coded packages of air packs and 5 coded packages of vacuum packs in refrigerator.
(4) Immediately irradiate 5 coded packages of air packs and 5 coded packages of vacuum packs at a radiation dose of 150 krad. (It is best to code the packages as to week of intended withdrawal, as well as the treatment).
(5) Place all packages in refrigerator.

7.1.4. Evaluation

(1) As soon as practicable remove the 4, zero storage time, samples from the refrigerator for evaluation.
(2) Aseptically open each package and remove an appropriate sample for microbiological analysis. Proceed as under (4) below.
(3) Quickly assess the quality factors indicated in the suggested evaluation chart using a scale for each factor selected by the instructor. To gain experience, these evaluations should be done and recorded by each individual.
(4) Make a microbiological analysis of the samle previously taken; (2) above.
(a) Aseptically weigh 10 g of sample into a sterile electric blendor jar containing 90 ml of sterile saline dilution water.

(b) Blend just long enough to obtain a homogeneous sample, but not long enough for the sample to heat up.

(c) Make appropriate dilutions by placing a measured amount of the homogenate into sterile dilution water, to obtain 3 decimal dilutions to give countable plates of bacterial colonies. The instructor should have sufficient background to make a selection of the dilutions required.

(d) Transfer the dilutions to sterile Petri plates and at once pour the total plate count agar into the plates and mix thoroughly.

(e) As soon as agar has solidified, invert the plates and place in the incubator at 30°C. (The instructor should explain why each step is taken, so the student may be fully aware of the reasons for the whole procedure, since the student will not be able to perform the microbiological examination for himself.)

(f) After 3 days of incubation visually examine the plates to see if they are ready for counting. If the plates are not being overgrown wait and count the plates after 5 days of incubation.

(g) Count plates having between 30 and 300 colonies and calculate the number present in each sample by multiplying the count by the dilution factor. Record the count for each sample.

7.1.5. Results

(1) Each week repeat the examination of samples using the same methods used for the zero storage time samples, section 7.1.4. (1) - (4).

(2) After the first week of storage the dilution used for the microbial examination of the irradiated and non-irradiated samples will have to be adjusted to take into account the changes in the microbial populations of the samples.

(3) Plot the results of the various factors studied in the entire experiment against the time of storage.

(4) From these curves determine the maximum extension of market life afforded by the packaging and the radiation treatment.

7.2. EXTENSION OF MARKET LIFE OF A FOOD BY IRRADIATION - Evaluation of extension of market life by radiation treatment of strawberries

7.2.1. Purpose

The purpose is to demonstrate the control of the growth of certain moulds on strawberries, by irradiation treatment, and thus retard spoilage during marketing.

7.2.2. Materials

(1) 20 commercial boxes of strictly fresh strawberries that show no evidence of spoilage

(2) Refrigerator, set for 10°C, and having a pan of water to provide fairly high atmospheric humidity

7.2.3. Procedure

(1) Irradiate 5 boxes at 100 krad,
Irradiate 5 boxes at 200 krad,
Irradiate 5 boxes at 300 krad.
(2) Place 4 coded boxes of each of the above in the refrigerator.
(3) Place 4 coded boxes of unirradiated fruit in incubator.
(4) Set aside 1 box of each of the above treatments for taste testing.

7.2.4. Results

(1) Prepare coded berries from the boxes above, (4), for testing by the trainees and ask them to evaluate the flavour score of each berry. Record the combined scores for each treatment.
(2) After 3 days of storage in the refrigerator examine all boxes for evidence of moulding or spoilage. Do not disturb the berries in the boxes. Record results.
(3) On each succeeding day examine the boxes for evidence of moulding and record results.
(4) When there is evidence of moulding, to an extent that there is definite sign of deterioration that would impair the market value, pour the berries out of the boxes and examine individually.
(5) Record number of berries showing (a) marked moulding, (b) some moulding, (c) trace of moulding and (d) no moulding.
(6) Calculate the percentage of berries showing these four categories in each box.
(7) Determine the treatment giving the best results and estimate the possible extensions of market life.

LABORATORY EXERCISE 8

8. SENSORY EVALUATION OF EFFECT OF IRRADIATION ON GROUND BEEF

8.1. Purpose

The purpose of this exercise is to, (a) demonstrate the effect of ionizing radiation on the flavour of meat, (b) possible changes in processing that would minimize the effect and (c) demonstrate procedure in the sensory evaluation of a food to determine consumer acceptance.

8.2. Materials

(1) Ground beef sufficient for experiment
(2) 22 metal, enamel-lined cans
(3) Chilling and freezing facilities
(4) Facilities for broiling meat

8.3. Procedure

(1) Fill the 22 cans with ground meat.
(2) Seal 14 of the cans at atmospheric pressure, and chill to 0°C.
    (a) Place 2 of the cans in the refrigerator as controls.
    (b) Freeze 4 cans at -17°C (solidly frozen).
    (c) Freeze 4 cans, in liquid air or liquid nitrogen, at -30°C (solidly frozen).
    (d) Irradiate at 200 krad:
        2 cans at 0°C
        2 cans at -17°C
        2 cans at -30°C
    (e) Irradiate at 4.5 Mrad:
        2 cans at 0°C
        2 cans at -17°C
        2 cans at -30°C
(3) Seal 8 of the cans under a high vacuum (draw vacuum more than once to remove all the oxygen).
    (a) Freeze 4 of these cans at -30°C
    (b) Irradiate at 200 krad:
        2 cans at 0°C
        2 cans at -30°C
    (c) Irradiate at 4.5 Mrad:
        2 cans at 0°C
        2 cans at -30°C
(4) Place all of the coded cans at 0°C, until tested.

8.4. Results

(1) Within 4 days after the irradiation (but not on the first day) open all cans.

(2) Before removal of meat from the can record the odour, colour and appearance of the meat, according to scales provided by the instructor.

(3) Remove meat from can, cut lengthwise and record any differences noted from observation made before removal, (2) above.

(4) Prepare thin patties from the meat from each coded lot, and cook under an electric broiler until done. Try to keep the cooking procedure as uniform as possible and serve hot. Present one patty to each student for evaluation.

(5) Evaluate the cooked meat for:

odour, colour, texture and flavour, using the 9 point hedonic scale.

(6) Combine the scores of all panel members for each treatment and determine the mean score. This should give an idea of the effect of the various treatments on the quality of the product.

If the differences in mean scores do not lend themselves to reaching a conclusion as to the effect of the treatments the instructor will assist you in further statistically analysing the results by use of the test known as analysis of variance.

9. EVALUATION OF EFFECT OF IRRADIATION ON MILK

9.1. Purpose

The purpose of this exercise is to demonstrate the keeping qualities of a food treated with different doses of radiation and the effect upon the flavour of the product.

9.2. Materials

(1) 16 containers of milk, fresh or pasteurized, with screw caps so containers can be opened, examined for odour, and resealed
(2) Refrigerator, set at 4°C

9.3. Procedure

(1) Prepare containers of milk.
(2) Irradiate 4 containers at each 0, 100 krad and 4.5 Mrad.
(3) Place in 4°C refrigerator.

9.4. Evaluation

(1) Make an evaluation of a container of each treatment on zero day of storage and record results in a form similar to Table E.
(2) After 3 days of storage examine a container of each treatment.

TABLE E. RADIATION TREATMENT OF MILK

Storage (d)	Unirradiated				Irradiated			
	Colour	Odour	Flavour	Condition	Colour	Odour	Flavour	Condition
0								
3								
5								
6								
7								
10								
15								

(3) After 4 days of storage examine the untreated and the 100 krad samples only.
(4) Repeat this after the 5th day of storage. If either sample is definitely spoiled discontinue examination of that lot.
(5) After 6 days of storage examine all 3 lots. If the untreated sample is unspoiled retain the container and store further.
(6) After 7 days of storage examine the 100 krad sample. If it is not spoiled retain and sample on subsequent days.
(7) After 10 days of storage examine the 4.5 Mrad sample.
(8) After 15 days of storage examine the last 4.5 Mrad sample.

This experiment was designed in part to show that milk and dairy products do not lend themselves to radiation treatment for preservation, because of the development of off flavour. Also, this product offers no health hazard from taste testing due to the nature of the milk itself and the 4°C storage temperature selected.

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